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An Evaluation of the Disposal of Flue Gas Desulfurization Wastes in Mines and the Ocean: Initial Assessment

Arthur D. Little, Inc, Cambridge, Mass

Prepared for

Industrial Environmental Research Lab, Research Triangle Park, N C

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AN EVALUATION OF THE DISPOSAL OF FLUE GAS DESULFURIZATION WASTES IN MINES AND THE OCEAN
Initial Assessment

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16. ABSTRACT

The report gives an initial assessment of the feasibility of disposing of flue gas desulfurization wastes in mines and in the ocean. The purpose of the assessment was to evaluate environmental, technical, regulatory, and economic aspects of the use of such disposal sites. Available data on chemical and physical properties of both treated and untreated sludges generated in ongoing environmental and privately funded sludge characterization programs were also collected and summarized. The report is based on data available through January 1976. The assessment is the first of a three-phase program. Phase 2 involves a refinement of the initial assessment, based on laboratory tests focused on key disposal impact issues. Phase 3 will involve pilot demonstration/simulation testing of viable mine and ocean disposal alternatives.

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AN EVALUATION OF THE DISPOSAL OF FLUE GAS DESULFURIZATION WASTES IN MINES AND THE OCEAN:
Initial Assessment

by

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ABSTRACT

This report presents an initial assessment of the feasibility of the disposal of flue gas desulfurization wastes in mines and in the ocean. The study was conducted by Arthur D. Little, Inc. for the Industrial Environmental Research Laboratory of the U.S. Environmental Protection Agency under Contract No. 68-03-2334. The purpose of the assessment was to evaluate the environmental, technical, regulatory, and economic aspects of the use of such disposal sites. As a part of this study, available data on the chemical and physical properties of both treated and untreated sludges generated in ongoing governmental and privately funded sludge characterization programs were also collected and summarized. The report is based upon data available through January 1976.

This assessment represents the first phase of a three-phase program. The second phase of work involves a refinement of the initial assessment based upon laboratory tests focused on key disposal impact issues. The third phase will involve a demonstration/simulation testing of viable mine and ocean disposal alternatives. Future reports will be issued covering these later phases of the work.

TABLE OF CONTENTS

PAGE

ABSTRACT iii
LIST OF TABLES vii
LIST OF FIGURES ix
ACKNOWLEDGMENTS xi
CONVERSION FACTORS xii
I. INTRODUCTION 1
  A. BACKGROUND 1
  B. PURPOSE AND OBJECTIVES OF THE STUDY 4
  C. CONTENT OF THE REPORT 6
  REFERENCES 7
II. CONCLUSIONS AND RECOMMENDATIONS 9
  A. MINE DISPOSAL 9
  B. OCEAN DISPOSAL 15
III. EXECUTIVE SUMMARY 21
  A. CHEMICAL AND PHYSICAL CHARACTERISTICS OF FGD SLUDGES 21
  B. MINE DISPOSAL 23
  C. OCEAN DISPOSAL 37
  D. ECONOMICS OF CONCEPTUAL DISPOSAL SYSTEM DESIGNS 48
  REFERENCES 50
IV. CHARACTERISTICS OF FGD SLUDGES 51
  A. CHEMICAL CHARACTERISTICS OF UNTREATED FGD SLUDGES 51
  B. PHYSICAL AND ENGINEERING PROPERTIES OF UNTREATED FGD SLUDGES . . . 60
  C. EFFECTS OF TREATMENT ON THE PHYSICAL AND ENGINEERING PROPERTIES OF FGD SLUDGES . . . 69
  D. EFFECTS OF TREATMENT ON POLLUTANT MIGRATION FROM FGD SLUDGES . . . 73
  REFERENCES 81
V. MINE DISPOSAL OF FGD SLUDGE 83
  A. REVIEW OF THE MINING INDUSTRY 83
  B. DISPOSAL OF FGD SLUDGE IN SURFACE COAL MINES 109
  C. DISPOSAL OF FGD SLUDGE IN UNDERGROUND MINES 132

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TABLE OF CONTENTS (Continued)

PAGE

D. DISPOSAL OF SLUDGE IN SELECTED UNDERGROUND MINERAL MINES . . . 157
E. FGD SLUDGE AS A TAILINGS AMENDMENT . . . 162
F. ASSESSMENT OF THE TECHNOLOGY . . . 171
G. ASSESSMENT OF REGULATORY ENVIRONMENT RELATIVE TO FGD SLUDGE DISPOSAL . . . 189
H. CONCLUSIONS AND RECOMMENDATIONS . . . 207
GLOSSARY . . . 213
REFERENCES . . . 216

VI. OCEAN DISPOSAL . . . 219
A. DESCRIPTION OF OCEAN ENVIRONMENT . . . 219
B. DESCRIPTION OF THE REGULATORY ENVIRONMENT . . . 229
C. FATE AND EFFECTS OF FGD SLUDGES ON THE CONTINENTAL SHELF . . . 235
D. FATE AND EFFECT OF FGD SLUDGES IN THE DEEP OCEAN . . . 255
E. ASSESSMENT OF TECHNOLOGY . . . 260
F. CONCLUSIONS AND RECOMMENDATIONS . . . 281
GLOSSARY . . . 284
REFERENCES . . . 288

VII. DISPOSAL SYSTEM COSTS . . . 291
A. BASIS FOR DESIGN AND ECONOMICS . . . 291
B. COAL MINE DISPOSAL . . . 291
C. OCEAN DISPOSAL . . . 300

LIST OF TABLES

TABLE NO. PAGE

I-1 Projected Sludge Production 4

IV-1 Major Components in FGD Sludge Solids 55

IV-2 Concentrations of Trace Elements in FGD Sludges 56

IV-3 Levels of Chemical Species in FGD Sludge Liquors and Elutriates 58

IV-4 True and Bulk Densities of FGD Sludge Solids 63

IV-5 Permeabilities of Untreated FGD Sludges 67

IV-6 Effect of Sludge Treatment on Bulk Density 71

IV-7 Effect of Sludge Treatment on Permeability 72

IV-8 Unconfined Compressive Strengths of Treated FGD Sludges 74

IV-9 Comparison of the Chemical Constituents in Sludge Liquors with Leachate after 50 Pore Volume Displacements 78

IV-10 Comparison of the Chemical Constituents in Eastern Limestone Sludge Leachate with Chemfix Chemically Treated Sludge Leachate 79

V-1 Land Utilized and Reclaimed by the Mining Industry in the United States in 1930-71 and 1971, by Selected Commodity . . . 84

V-2 Production of Bituminous Coal and Lignite in U.S. by Region Underground, Strip and Auger Mining (1973) 88

V-3 Number of Coal Mines by States (1973) 89

V-4 Number of Domestic Metal and Nonmetal Mines in 1973, by Commodity and Magnitude of Crude Ore Production 97

V-5 Production of Ore in the U.S. by Mining Method - 1971 for the Major Mineral Commodities 98

V-6 General Types of Metal and Nonmetal Mines as Related to Geologic Nature of Deposits 100

V-7 Coal Mines - Screening for Acceptability for FGD Disposal . . . 105

V-8 Metal and Nonmetal Mines - Screening for Acceptability for FGD Disposal 106

LIST OF TABLES (Continued)

TABLE NO. PAGE

V-9 Mine Drainage Classes 149

V-10 Comparative Properties of Potential Tailing Amendments 170

V-11 Comparison of Water Quality Criteria and Practical Range of Measurement Methodology 186

VI-1 Major Constituents of Seawater 222

VI-2 Toxic Heavy Metals of Importance in Marine Pollution Based on Their Seawater Concentration and Toxicity 223

VI-3 Approved Interim Ocean Dumping Sites, East and Gulf Coasts . . 226

VI-4 Trace Contaminant Concentrations in Reported Sludge Liquors from Eastern Coals and NAS Minimal Risk Criteria for the Marine Environment 249

VI-5 Concentrations of Trace Elements in Sludge Solids and "Minimal Risk Criteria" 252

VII-1 Sludge Basis for Conceptual Design 292

VII-2 Capital Cost Basis (1978 Completion) 293

VII-3 Unit Cost Factors 294

VII-4 Capital and Operating Costs for Mine Disposal Alternatives . . 301

VII-5 Capital and Operating Costs for Ocean Disposal Alternatives (Bottom-Dump Disposal) 306

LIST OF FIGURES

FIGURE NO. PAGE

I-1 Power Plants in the U.S. over 100 Mw in Size Having Coal Burning Capability (1975) 2

IV-1 Particle Size Distribution of FGD Sludges 61

IV-2 Viscosity of Desulfurization Sludge 63

IV-3 Relationship between Compressive Strength and Curing Time for Sludge Treated with Fly Ash and Quicklime (Ontario Hydro) . 75

IV-4 Relationship between Compressive Strength and Curing Time for Sludge Treated with Fly Ash and Cement (Ontario Hydro) . . 76

V-1 Coal Fields of the United States 85

V-2 Mining Methods Used in U.S. Bituminous Coal Production 87

V-3 Area Strip Mining with Concurrent Reclamation 90

V-4 Contour Coal Stripping 92

V-5 Block Methods of Contour Strip Mining 93

V-6 Types of Underground Coal Mines 94

V-7 Area Coal Stripping 111

V-8 Cross Section - Operating Strip Coal Mine 112

V-9 Cross Section - Western Strip Mine 115

V-10 Contour Backfill 118

V-11 Regional Groundwater Movement in Surface Coal Mines 123

V-12 Conventional Room and Pillar Coal Mining Main Haulage - Conveyor 134

V-13 Typical Longwall Mining Cross-Sections Showing Caving Action . 135

V-14 Longwall Stowing - Conventional 138

V-15 Plan - Room and Pillar Mine 140

V-16 Seismic Risk Areas and Fault Zones in the United States 144

V-17 Regional Groundwater Movement in Sealed Underground Mines . . . 153

LIST OF FIGURES (Continued)

FIGURE NO. PAGE

V-18 Blind Hydraulic Flushing of Abandoned Lead-Zinc Mine 159

V-19 Longwall Stowing - Lateral 183

VI-1A Atlantic Coastal Waters and Dump Sites 220

VI-1B Gulf Coastal Waters and Dump Sites 221

VI-2 Pathways of Interactions in a Simplified Ocean Dumping Scenario 227

VI-3 Schematic Diagram Showing Transport Processes - Hinged Bottom-Dump Barge 236

VI-4 Observed Sulfite Oxidation Rates 246

VI-5 Factors Contributing to the Cumulative Distribution of Dumped Sludge 256

VII-1 Surface Mine Disposal Operations 295

VII-2 Underground Mine Disposal Operations 298

VII-3 Ocean Disposal Operations 302

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CONVERSION FACTORS

English/American Units	Metric Equivalent
Length:	
1 inch	2.540 centimeters
1 foot	0.3048 meters
1 fathom	1.829 meters
1 mile (statute)	1.609 kilometers
1 mile (nautical)	1.852 kilometers
Area:	
1 square foot	0.0929 square meters
1 acre	4,047 square meters
Volume:	
1 cubic foot	28.316 liters
1 cubic yard	0.7641 cubic meters
1 gallon	3.785 liters
Weight/Mass:	
1 pound	0.4536 kilograms
1 ton (short)	0.9072 metric tons
Pressure:	
1 pound per square inch	0.07031 kilograms per square centimeter
Concentration:	
1 part per million (weight)	1 milligram per liter
Speed:	
1 knot	1.853 kilometers per hour
Energy/Power:	
1 British Thermal Unit	1,054.8 joules
1 megawatt	3.600 x 10^9 joules per hour
Temperature:	
1 degree Fahrenheit	5/9 degree Centrigrade

I. INTRODUCTION

A. BACKGROUND

There are now more than 1,000 fossil fuel-fired steam electric plants operating in the United States. Of the total generating capacity amounting to well over 300,000 megawatts, roughly 200,000 megawatts have been designed to fire coal either exclusively or as an option with oil and/or gas. The map in Figure I-1 shows the distribution of plants over 100 megawatts in the United States as of 1975 that have the capability of firing coal. The plants shown include all those originally designed to burn coal, except for those which are known to have been converted to either oil or gas burning exclusively (primarily plants in eastern metropolitan areas, such as New York City).

The vast majority of the coal-fired capacity is located in the eastern section of the country, an area rich in high sulfur coal. For the most part, eastern plants have burned locally available high sulfur coal. In recent years low sulfur has accounted for less than 30% of the total coal burned in eastern power plants. More than half of the eastern low-sulfur coal has been channeled into metallurgical markets.

A number of studies have been conducted in the last five years to project the need for flue gas desulfurization (FGD) systems to control emissions of SO_2 and determine the capability of equipment suppliers to meet these needs (1,2,3,4). These studies have generally focused on coal-fired capacity because of the increasing use of coal, uncertainty in the oil supply situation, and the greater ease with which oil-fired plants can switch to low-sulfur oil, if available. In 1975 the U.S. Environmental Protection Agency (EPA) estimated the cumulative need for FGD systems on utility boilers to be about 65,000 megawatts of coal-fired generating capacity (1), and that by the end of 1980 the need would rise to about 90,000 megawatts. Taking into account industrial boilers and oil-fired plants, the need could easily exceed 100,000 megawatts by 1980.

However, the installation of FGD systems is expected to lag behind this anticipated need. Presently the capacity of operational FGD systems totals less than 6,500 megawatts. And, based upon current trends, the

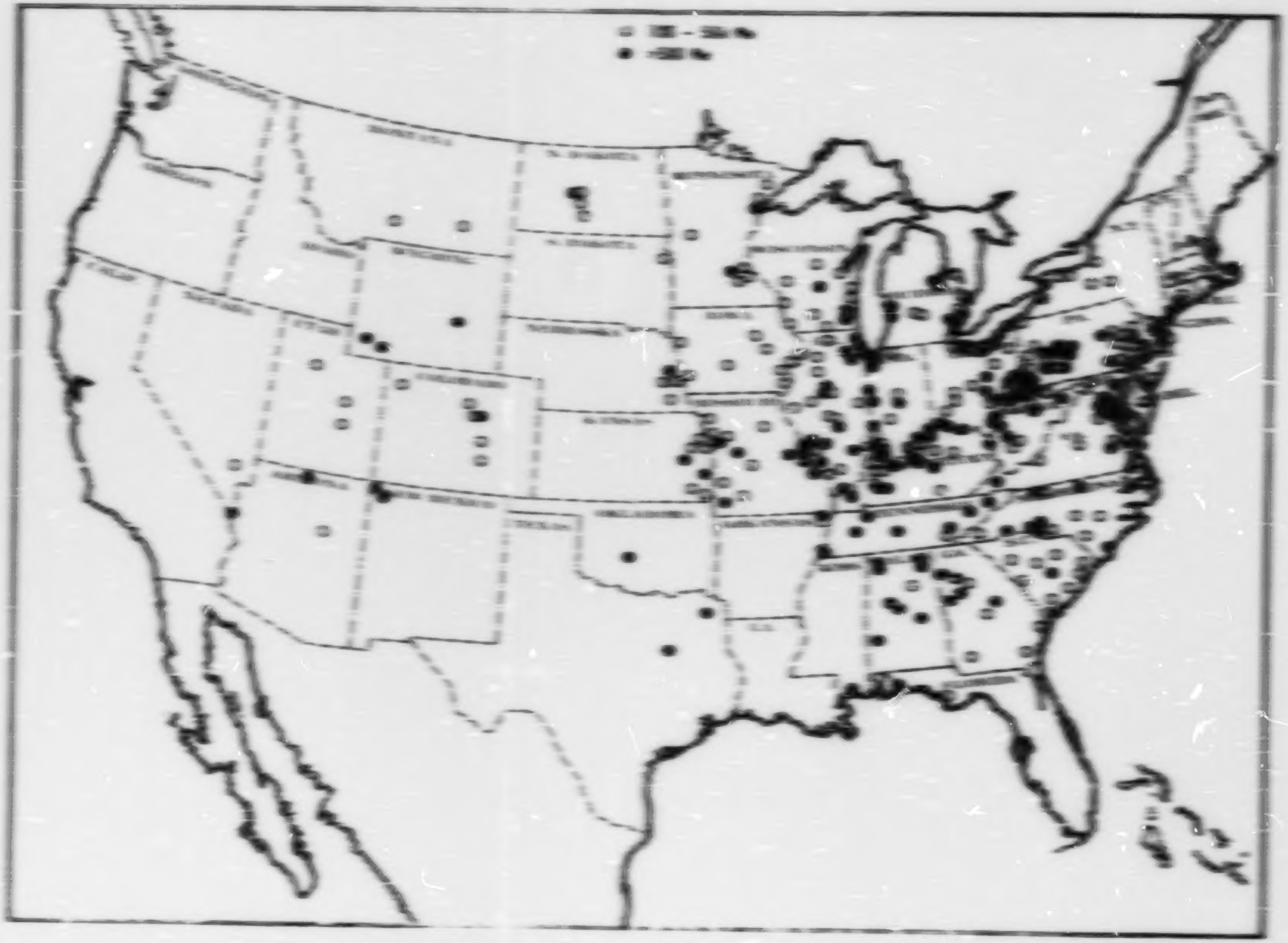
○ 100 - 500 Mw
● >500 Mw

FIGURE I-1 POWER PLANTS IN THE U.S. OVER 100 Mw IN SIZE HAVING COAL BURNING CAPABILITY (1975)

capacity of operational FGD systems may reach only about 35,000 megawatts by 1980. By 1985, the figure could exceed 100,000 megawatts.

Better than 90% of the FGD capacity now in service and under construction involves non-regenerable (waste producing) FGD technology, a trend which is expected to continue through 1985. The principal non-regenerable systems produce solid waste (sludge) and fall into the following four general categories: direct lime scrubbing, direct limestone scrubbing, fly ash scrubbing, and dual alkali systems (scrubbing with a soluble sodium absorbent followed by regeneration of the absorbent with lime).

Both the character and quantity of the sludge produced by these systems vary widely depending upon the operating conditions of the boiler, the sulfur content of the coal, and the type and design of the scrubber system. In general, the sludge consists of mixtures of calcium sulfate (as $CaSO_4 \cdot 2H_2O$ or $CaSO_4 \cdot 1/2H_2O$), calcium sulfite (as $CaSO_3 \cdot 1/2H_2O$), and lesser amounts of unreacted lime or limestone, as well as small but significant quantities of soluble constituents (e.g., calcium and sodium salts). Many also contain fly ash which can be simultaneously removed with SO_2 in the scrubbers and/or admixed with the SO_2 scrubber sludge.

The amount of dry, ash-free sludge can range from as low as about 40 lbs/megawatt-hour (<5% by weight of the coal burned) in low-sulfur coal applications to greater than 160 lbs/megawatt-hour (<20% by weight of the coal burned) for high-sulfur coal applications. Table I-1 shows projections of sludge production for the years 1980 and 1985, assuming 35,000 megawatts and 100,000 megawatts installed capacity, respectively. Assuming an average annual load factor for all plants of 70%, the amount of wet sludge including fly ash (50% solids) would total about 40 million short tons in 1980 and about 110 million short tons in 1985. These figures are based upon a distribution of FGD system by capacity of roughly 50% limestone, 40% lime and dual alkali, and 10% fly ash scrubbing. This distribution reflects the increasing use of limestone scrubbing systems, particularly in medium- and low-sulfur coal applications.

TABLE I-1

PROJECTED SLUDGE PRODUCTION

Year	1980	1985
Assumed On-Line Capacity (Mw)	35,000	100,000
Dry FGD Sludge (thousands of short tons/year)	8,500	24,500
Dry Ash (thousands of short tons/year)	10,500	30,000
Total Dry (thousands of short tons/year)	19,000	54,500
Water (@ 50%) (thousands of short tons/year)	19,000	54,500
Total Wet Sludge (thousands of short tons/year)	38,000	109,000
Approximate Total Volume (acre-feet/year)	~20,000	~60,000

A principal concern with the widespread application of non-regenerable systems is the disposal of the large quantities of sludge produced. Most utility installations of nonregenerable FGD systems now in operation in the United States employ disposal methods involving some form of on-site ponding or impoundment of the sludge. The earliest systems used unlined disposal areas. Many recently installed systems use lined areas, and some include chemical treatment of the wastes to improve structural properties and reduce the mobility of potential pollutants. Aside from the possible adverse chemical/biological impacts, the use of ponds, landfills, and impoundments may be limited by the large tracts of land required, land that may not be readily available. Depending upon the sulfur content of the coal (and ash content), the land requirement for disposal can range from as low as 0.25 acre-feet/megawatt-year to greater than 1.0 acre-feet/megawatt-year. In the Northeast such land requirements can pose significant limitations on the burning of any high-sulfur fuel.

B. PURPOSE AND OBJECTIVES OF THE STUDY

The purpose of this study, therefore, is to evaluate the feasibility of mines and the ocean as alternative sites to ponds and landfills for the disposal of FGD sludge. This report presents the results of the initial assessment of the technical, environmental, regulatory, and economic aspects of these alternatives.

Specific objectives of the study were to:

- outline available data on the chemical, physical, and engineering properties of both treated and untreated sludges and potential for pollutant mobility in order to provide a data base for the assessment effort;
- evaluate the potential fate of sludges in mine and ocean environments, including the identification of physical, chemical, and biological impacts of concern, and, to the extent possible, determination of realistic disposal criteria;
- review the state-of-the-art of technology related to disposal operations with emphasis on detection, monitoring, and control, as appropriate.
- investigate possible benefits that may result from disposal operations (e.g., subsidence control, use of sludge as a tailings amendment);
- review and assess federal and stage regulations, focusing on their adequacy for protecting the environment; and
- develop concepturlized designs and prepare preliminary estimates of capital and operating costs for representative, feasible disposal operations.

While the scope of the study is quite broad, the focus is on the environmental assessment. It serves as the basis for developing disposal criteria, defining and evaluating relevant technology, formulating conceptual disposal schemes, and assessing the adequacy of existing regulations for protecting the environment. The overall assessment approach is basically a three-step process involving: (1) grouping of disposal sites by characteristic conditions and/or regions (e.g., deep versus shallow ocean, western versus eastern mines, strip versus deep mines, etc.); (2) evaluation of the fate (impact) of untreated sludge for an assumed simple disposal operation; and (3) evaluation of the effects of controlling the disposal by limiting or altering sludge properties, adjusting the method of placement, or imposing indirect measures to minimize impacts. As appropriate and to the extent allowed by the available sludge data, the assessment has taken into account the variability in principal sludge characteristics according to region (type of coal) and type of FGD system.

By design, this approach provides a general assessment of the feasibility of the disposal of FGD sludge in mines and in the ocean, and the identification of those options which appear to be most promising. Any decision regarding the viability of a particular disposal operation should be based upon the pertinent site-specific and sludge-specific conditions--an assessment which is beyond the intent and scope of this study.

This initial assessment represents the first phase of a three-phase program. The second phase will involve laboratory studies related to certain key impact issues identified in the first phase, and an update and refinement of the initial assessment. The third phase will involve additional testing and simulation or demonstration of promising ocean and mine disposal options.

C. CONTENT OF THE REPORT

The report contains six chapters following this introduction.

- Chapter II presents the conclusions and recommendations of this initial assessment.
- Chapter III is a topical summary of the report.
- Chapter IV is a review of the available data on FGD sludge properties, used as a data base for this assessment.
- Chapter V contains the assessment of the disposal of FGD sludges in mines, including:
  - physical, chemical, and biological impacts;
  - potential benefits;
  - status of disposal technology; and
  - adequacy of regulations and responsibility of regulatory programs.
- Chapter VI contains the assessment of the disposal of FGD sludges in the ocean, including:
  - physical, chemical, and biological impacts;
  - status of disposal technology; and
  - adequacy of regulations.
- Chapter VII summarizes capital and operating costs for conceptualized designs for representative disposal schemes.

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II. CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations are presented in two parts. The first part gives the conclusions of the environmental, technical, and regulatory assessments and the need for additional research and information regarding the use of mines for the disposal of flue gas desulfurization (FGD) wastes. The second part gives the analogous conclusions and recommendations for the assessment of the ocean disposal of FGD wastes.

A. MINE DISPOSAL

1. Technical/Environmental Considerations

The overall conclusion from this assessment of the disposal of FGD sludges in mines is that while promising from both a technological and an environmental standpoint, such disposal operations can result in significant environmental impacts and each proposal for FGD sludge disposal must be assessed on a case-by-case basis to determine the magnitude and acceptability of these impacts. The fate of the sludge and the extent of the environmental impacts will depend primarily on the geology of the particular disposal site and on the specific characteristics of the sludge but also on the indigenous quality of receiving groundwaters and potential pathways to surface waters.

Specific conclusions of the assessment are as follows:

- There is sufficient available space in the United States being generated annually in active mines for disposal of all FGD sludge. Individual coal mines in most cases have space available to dispose of at least the amount of sludge produced from the coal extracted.

  Mines employing surface stripping or underground conventional room and pillar operations are the most promising because of their accessibility and availability of space. Open pit mines are generally not promising because use of the space would hinder access to mineral reserves. Underground mines employing caving (by longwall, pillar robbing, or

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stoping) have limited promise because they lack available space. By production and available space, the most promising categories of active mining for accepting sludge are ranked as follows:

1. surface coal mining;
2. underground room and pillar coal mining;
3. underground room and pillar limestone mining;
4. underground room and pillar lead-zinc mining;
5. underground room and pillar salt mining; and
6. underground longwall coal mining.

- Placement and handling techniques for FGD sludge disposal in both surface and underground mines are available and have been demonstrated for disposal of other materials in mines (i.e., coal refuse), although the techniques may require modifications for application to FGD sludge disposal. There is the potential for significant disruption of ongoing mining operations due to the volume and physical properties of sludge to be handled. One potential physical impact of concern is liquefaction of the sludge either during disposal operations or after disposal is completed. However, sound engineering design of sludge placement, proper site selection, and constraints on sludge properties can control such impacts.
- The major potential adverse chemical impact of FGD sludge disposal in the vicinity of mining is increased constituent loadings (especially sodium and calcium chlorides and sulfates) to the mine drainage discharge. In areas removed from the influence of mine drainage pump-out the principal potential adverse chemical impact of FGD sludge is leachate contamination of groundwater. Leachate concentrations for treated and untreated sludges are generally expected to be within the ranges of concentrations of the chemical constituents in FGD sludge liquors for hundreds

of years due to the slow movement of groundwater. However, the significance of the impact on the groundwater will depend importantly on the quality of the groundwater and the total quantity of leachate produced as well as its concentration. This must be evaluated on a case-by-case basis relative to potential contaminant contributions to downgradient water supply wells and surface waters. In some cases the quality of the leachate would be no worse, and possibly better, than existing mine drainage, at least with regard to acidity and total dissolved solids (TDS).

- The generation of sludge leachate will be site-specific, with the greatest amounts produced when sludge is within a groundwater regime of high transmissivity (having a steep hydraulic gradient and high permeability). Attenuation of FGD sludge leachate is also site-specific, with the least attenuation in acidic groundwater environments having soil and rock of limited ion exchange capacity. Integrating these two factors, ranking of mining categories on a national perspective (in order of the most promising):
    1. underground limestone and coal room and pillar mines above the water table;
    2. coal surface area mines (Interior and Western);
    3. coal surface contour mines (Eastern);
    4. lead-zinc underground room and pillar mines; and
    5. coal underground room and pillar, and longwall mines within the water table (Eastern and Interior).

  Note: Salt mines were not specifically addressed within the scope of this study, even though they could receive the highest ranking. Salt mines have generally been assigned a higher priority with regard to the disposal of wastes, e.g., hazardous radioactive wastes.
- The generation of sludge leachate is also sludge-specific with decreasing amounts occurring with decreasing sludge

permeability (especially through compaction or chemical treatment). The concentrations of constituents in leachate is also sludge-specific, with concentrations tending to decrease as alkalinity increases, fly ash content decreases, and inorganic constituents originally present in coal decrease, i.e., chloride and trace metals.

- Discharge of sludge leachate to surface waters can adversely affect aquatic life by the addition of bioccumulative trace metals. In the case of sludges containing sulfite, there is the potential toxicity of dissolved sulfite itself as well as the potential depletion of dissolved oxygen due to the sulfite.
- In surface mines, control techniques to minimize groundwater contamination include decrease of sludge permeability through compaction or chemical treatment and placement of sludge outside the groundwater reservoir through modified disposal operations. In underground mines, the primary control technique is chemical treatment.
- The state-of-the-art of site monitoring and analytical techniques to predict and assess impacts is adequate for FGD sludge disposal. The general location of monitoring sites must be based upon geologic field surveys in order to develop appropriate background and leachate data.
- In underground mines, FGD sludge placement results in the potential benefits of lessening acid drainage formation and long-term subsidence, primarily by sealing exposed coal against air exposure which leads to pyritic sulfur oxidation and also leads to pillar deterioration.
- FGD sludge provides little potential as an amendment to mine tailings for enhancing vegetative growth. In this regard, FGD sludge generally ranks poorly in comparison to limestone and sewage sludge.

2. Regulatory Considerations

Recent shifts in regulatory attitudes show a growing concern for groundwater protection from seepage or leachate from the disposal of wastes. Given the recent Resource Conservation and Recovery Act of 1976, existing laws are legally adequate to insure protection of the geologic environment from waste disposal. However, because of the technical difficulties of completely characterizing an underground environment and of locating monitoring wells, regulation should rely on guidelines for site selection and waste acceptance and should allow for case-by-case assessment by professional geologists and geochemists.

Specific conclusions are as follows:

- The lead authorities for FGD sludge disposal appear to be the federal and state environmental protection agencies.
- The lead legislation is expected to be the Resource Conservation and Recovery Act of 1976, involving state resolution of Federally approved programs and the existing planning infrastructure established for 208 areawide wastewater management planning under the Federal Water Pollution Control Act Amendment of 1972.
- The combination of federal and state legislation is legally adequate to protect the environment during and after FGD sludge disposal; however, regulations are needed with site selection and waste acceptance guidelines based upon the characteristics of FGD sludge and research on potential environmental impacts.
- Additional legislation and standards may be required to protect worker health and safety. Administration of the health and safety requirements need clarification, especially between authorities of OSHA and MESA.
- Because of the non-point source nature of air and water emissions from FGD sludge disposal and the large variations in FGD sludge character, disposal should be regulated on a case-by-case basis.

3. Need for Additional Research and Information

The following research needs are believed most important at this time.

- Development of additional, more comprehensive physical and engineering properties data base and corroboration (or comparison) of results with field data. Of particular interest are:
  - triaxial compression tests for shear strength of untreated sludges to determine the ability to support loadings while unconfined;
  - dynamic triaxial compression tests for untreated sludges to simulate resistance to shear under seismic cyclic loadings applicable to various regions of coal reserves;
  - consolidation tests for untreated and soil-like treated sludges to simulate density and permeability under various static loadings related to overburden pressures; and
  - Atterberg limits for untreated sludges.

  Some of this testing is now underway in programs funded by EPA and other governmental agencies, and will be reviewed as available as a part of the Phase II effort.
- Development of a data base on key chemical impact issues relating to mine disposal. Of particular importance are:
  - the potential for TDS leaching from sludges and rates of TOS oxidation;
  - the potential for chemical attack of cement/concrete by sludge liquors and leachate;
  - the potential for SO_2 evolution during the initial stages of sludge disposal in underground mines with acidic environments;
  - the short-term effects of climate (e.g., freezing, excessive rainfall, etc.) on the physical properties of untreated sludges and pollutant mobility.

These will be addressed in Phase II. Where data are not available, appropriate laboratory tests will be performed.

- Laboratory or field testing relating to the handling, storage and placement techniques (including hydraulic and pneumatic stowing) to determine optimum sludge properties, preview technical difficulties and assess secondary environmental effects (e.g., creation of dust during handling, storage and placement). It is expected that these issues would be addressed, to the extent possible, during the simulation/demonstration testing in Phase III.
- Survey of dust, noise, airborne contaminants and other health and safety criteria affecting waste disposal operations, and clarification of the respective roles of health and safety regulatory authorities (e.g., OSHA and MESA).
- Field survey of various mines (especially coal, limestone, and lead-zinc) to develop a more extensive data base on the alkalinity/acidity of drainage, the extent of pillar robbing, the pathways and rate of groundwater flow, and the potential for long-term subsidence.

B. OCEAN DISPOSAL

1. Technical/Environmental Considerations

Two major overall conclusions emerge from this assessment of the disposal of FGD sludges in the ocean. First, there is an overriding need for case-by-case analysis of the environmental feasibility of ocean disposal of specific FGD sludges. The emphasis in such analyses should be twofold, focusing both on the type of sludge and disposal site environmental conditions. Second, control options involving chemical treatment of sludge, limitations on the type of sludge disposed of, and control of the method of sludge placement (either dispersed or concentrated bottom-dump disposal) all appear to be technically feasible. Economic feasibility, however, is less clear-cut and would serve to limit the viability of several of the most promising environmental options.

Specific conclusions are as follows:

- Unless further work contradicts the anticipated sedimentation and suspension impacts, the disposal of untreated or treated FGD sludges with soil-like physical properties by bottom-dump barge or outfall on the continental shelf must be considered to be environmentally unacceptable.
- Based upon available information on sulfite toxicity, it appears that an almost immediate (on the order of minutes) dilution factor greater than 10,000:1 for sulfite alone is required in the dispersed disposal of untreated sludges containing large fractions of sulfite. The technology is not currently available for attaining such dilution factors for untreated sulfite-rich sludges in an economical manner. Therefore, the dispersed disposal of sulfite-rich sludges, both on and off the continental shelf, is not considered to be a promising option at the present time. Further information on organisms uptake and toxicity of TOS could justify reevaluation of this conclusion.
- Several disposal options appear promising and are recommended for further research. These include:
  - dispersed disposal of untreated sulfate-rich FGD sludges on the continental shelf;
  - concentrated disposal of treated brick-like FGD sludge on the continental shelf;
  - dispersed disposal of untreated sulfate-rich FGD sludges in the deep ocean; and
  - concentrated disposal of both untreated sulfate-rich FGD sludges and treated FGD sludges in the deep ocean.

  Recommended additional research is discussed in more detail below.

2. Regulatory Considerations

In general, given the present vigilance in agency attitudes towards ocean dumping, the existing regulations appear to be adequate to insure protection of the ocean environment. However, several specific recommendations are considered appropriate at this time. These are as follows:

- Pending revisions to the existing ocean dumping regulations that would allow for additional empirical considerations (e.g., field data and models) in the determination of limiting permissible concentrations in the ocean at the disposal site should be adopted.
- Existing absolute limits on permissible concentrations of mercury and cadmium in solid fractions of wastes should be reevaluated through consideration of the actual anticipated long-term availability of the contaminants on a case-by-case basis.
- Inherent disincentives to deep ocean dumping (e.g., extra monitoring requirements) should be reevaluated in light of the apparent desirability of certain deep ocean disposal options.

There appears to be no need for additional sludge-related legislation concerning ocean disposal at this time.

3. Need for Additional Research and Information

The following research needs are believed most important at this time.

- A body of empirical data needs to be developed concerning the chemical and physical fate of sludge in seawater. Of particular importance are:
  - dissolution rates of various treated and untreated FGD sludges in the representative types of seawater that would characterize the disposal area environs; and
  - physical transport of both treated and untreated sludges in the water column during descent and subsequently in the marine benthos (near the bottom).

  These effects will be studied in laboratory-scale testing with untreated sludges during the Phase II program.

- A body of empirical data needs to be developed regarding the biological impacts of sludge disposal. Specifically:
  - uptake of both liquid and solid constituents of FGD sludges by various marine organisms need to be developed;
  - in particular, for uptake associated with short-term exposure of pelagic organisms; and
  - lethal and sub-lethal effects thresholds need to be developed for exposure of a variety of representative marine organisms to FGD sludges (one of the focal points of such research should be the dynamics of food web transfer of potential toxicants).

  The investigation of such biological impacts is planned for the simulation/demonstration testing in Phase III.
- Mechanisms for eliminating existing economic disincentives to deep ocean disposal should be developed. These could include consideration of such options as a greater federal role in baseline and disposal area monitoring.

III. EXECUTIVE SUMMARY

A. CHEMICAL AND PHYSICAL CHARACTERISTICS OF FGD SLUDGES

Both the chemical composition and the physical and engineering properties of the sludge produced by any given FGD process at any particular time depend upon a large number of factors including: the composition of the coal burned, the type of boiler and its operating conditions, the method of particulate control employed, and the type of FGD system employed and the way in which it is operated. Sludge characteristics, therefore, and the chemical composition in particular, can vary over extremely wide ranges. The most extensive studies characterizing sludges are being conducted by the Aerospace Corporation (Aerospace) and the United States Army Corps of Engineers Waterways Experiment Station (WES) for the U.S. Environmental Protection Agency (EPA). Although these programs are still underway, the data are sufficient to establish the range of sludge characteristics that might be encountered. Additional data will be required, however, to predict the characteristics of sludge produced by a particular process or process type under a given set of conditions, and more extensive testing of physical and engineering properties is necessary to accurately predict the behavior of sludges in actual disposal operations.

1. Chemical Composition of FGD Sludges

The principal substances making up the solid phase of FGD sludges are calcium-sulfur salts (calcium sulfite and/or calcium sulfate) along with varying amounts of calcium carbonate and fly ash. The ratio of calcium sulfite ($CaSO_3 \cdot 1/2\ H_2O$) to calcium sulfate (present as $CaSO_4 \cdot 1/2\ H_2O$ or gypsum, $CaSO_4 \cdot 2H_2O$) can vary over an extemely wide range depending upon the extent to which oxidation occurs within the system. Oxidation is generally highest in systems installed on boilers burning low sulfur coal or in systems where oxidation is intentionally promoted. Fly ash will be present in the sludge if the scrubber also serves as a particulate control device or if separately collected fly ash is admixed with the sludge. Varying amounts of unreacted limestone (up to 40%) can be found in sludges produced from direct limestone scrubbing. In direct lime of dual alkali process sludges, $CaCO_3$ is often present in smaller amounts due to impurity in the reagent lime, reaction with small amounts of absorbed CO_2 or solution softening with sodium carbonate.

A variety of trace elements find their way into FGD sludges from a number of sources: from coal where they are present either in mineral impurities or as organometallic compounds; from lime, limestone, or other reagents used in the FGD system; and even from the process makeup water used. The levels of trace elements found in the sludge depend primarily upon their level in the coal, the amount, if any, of ash that is collected or admixed with the sludge, and the efficiency of the scrubber system in capturing trace metal vapors. The range of concentrations that have been measured in a variety of sludge samples cover two orders of magnitude and are similar to the range of concentrations found in coal (1,2,3). For sludges containing fly ash the concentrations of the most prevalent trace metals (cadmium, manganese, zinc, etc.) can range as high as a few hundred parts per million (ppm).

The liquid phases of FGD sludges contain dissolved in them a variety of substances ranging from traces of a variety of metals to substantial amounts of commonly occurring ions like sodium, calcium, chloride, and sulfate. As was the case with the composition of sludge solids, concentrations of soluble substances in sludge liquors can vary by two orders of magnitude or more. The total dissolved solids (TDS) level can vary from about 2,500 mg/liter to as much as 100,000 mg/liter depending on the chloride/sulfur ratio in the coal, the type of system, and the extent to which the solids are dewatered (and washed), if at all (1,2). However, because of the insolubility of many of the trace metal hydroxides, only a very small fraction of the total amount of almost every trace metal present in the sludge is found dissolved in the sludge liquor.

2. Physical and Engineering Properties of Untreated FGD Sludges

The physical and engineering properties used to characterized FGD sludges have generally been those which have proven useful in characterizing and predicting the behavior of soils in construction and landfill operations. The most commonly used tests include particle size distribution, bulk density, unconfined compressive strength, compaction moisture/density relationships, viscosity, permeability, and leaching behavior. To date, there has been little work involving triaxial compression testing, consolidation behavior, or Atterberg limits.

Determinations of particle size distribution by sedimentation carried out at WES indicated that for most sludges the particle size distributions fell in the range of 5-50 microns, a range corresponding to silty to sandy soil. However, particles both smaller (less than 1 micron) and larger (at least 200 microns) have been observed (4). The true densities of the solid particles themselves range from about 2.1 to about 2.6 g/ml (1,2,5). But, depending upon the quantity of liquor present and the amount of entrained air, the specific gravity of the product sludge can range from about 1.3 to 1.8.

The viscosity of an FGD sludge increases as the solids content increases, although the exact relationships depend on the particular material (particle size distribution, crystalline morphology, and the quantity of ash present) as dictated by process type and operating conditions. The highest viscosities were observed for agglomerated sulfite-rich crystals such as those produced by dual alkali systems (which become difficult to pump at greater than 40% solids), and the lowest viscosities were observed for sludges containing a high fraction of gypsum. Increasing amounts of fly ash seemed to reduce the viscosity, perhaps because the spherical particles act as ball bearings (1).

The extent to which FGD sludges can be dewatered also depends upon the size and shape of the crystals as well as the dewatering process. Sulfite-rich sludge can typically be thickened to 20% to 40% solids and filtered to 35% to 80% solids. Sulfate-rich sludge can usually be thickened to 30% to 60% solids and filtered to 60% to 90% solids.

If the solids content of FGD sludges is increased sufficiently by filtration, centrifugation, or by other means such as addition of a dry material, they are amenable to compaction into a material which can be quite firm and which, if confined, can support considerable weight. Maximum dry bulk densities of about 70-85 lbs/cubic foot have been observed for sludges compacted according to the Proctor method (5,6). While sludges compacted in this manner are quite firm, they have very little load-bearing strength when the restraining mold is removed. Measurements of unconfined compressive strengths have ranged from nil to 20 lbs/square inch.

Coefficients of permeability have been measured for both compacted and uncompacted sulfite- and sulfate-rich sludges. Measured values generally fall in the range of about 10^{-4} to 10^{-5} cm/second.

3. Effects of Treatment on Sludge Properties

A variety of treament processes have been developed for altering the physical properties of FGD sludges. Depending upon the kind and amount of reagent added during treatment, the treated material can become reasonably hard with low permeabilities after it cures, or it can be a dry, soil-like material which can harden after compaction.

While most processes currently being offered are considered proprietary, the addition of lime and fly ash, or a similar source of silicate, is believed to be the basis for one or more of the available treatment technologies. Lime and a silicate-containing material undergo a pozzolanic reaction in which calcium from the lime reacts with silica to produce a cementitious calcium-silicate matrix which gives strength to the treated mass and reduces its permeability. Treatment processes of the sort which produce a relatively hard material generally exhibit unconfined compressive strengths in the range of 100-400 lbs/square inch (4,5), although one treatment process included in the WES program resulted in unconfined compressive strength of nearly 5,000 lbs/square inch. Unconfined compressive strengths of soil-like materials, after being remolded and Proctor compacted, ranged from 20-50 lbs/square inch (4).

Preliminary data on leaching potential obtained from accelerated laboratory leach tests and field testing in small ponds (1,2,7) indicate that treatment can reduce the concentration of total dissolved solids and the predominant soluble ions which constitute the TDS in leachates. Whether or not the concentrations of trace substances are reduced has yet to be established with any degree of certainty. In some cases, reported concentrations of certain trace elements have actually been higher in leachates from treated sludge. However, treatment processes still hold promise for reducing the pollutant potential of sludges. Decreasing the permeability can, in and of itself, be a significant factor in reducing pollutant mobility. But there is also the possibility that major soluble substances are immobilized. And the improved handling properties of treated sludges may permit better control of sludge placement and, in the case of ponds, of surface contours which can result in better control of surface water runoff.

B. MINE DISPOSAL

1. Screening of Mine Alternatives

There are over 15,000 mines in the United States today which together produce over one-half billion tons of coal and 2.5 billion tons of metallic and nonmetallic minerals. About one-third of these mines individually produce over 100,000 tons/year.

To focus on the most promising alternatives, mines have been broadly grouped according to region, mineral mined, mine capacity, and method of mining; and each group has been screened with regard to overall technical feasibility. The screening process considered the capacity for sludge, ease of disposal, prevention of future resource recovery and general proximity to sludge sources. This screening is derived from a national perspective and does not consider small mines having site-specific conditions favorable to sludge disposal.

a. Coal Mines

About one-half of the coal currently produced in the United States is surface mined, and one-half is produced from underground mines. The vast majority of coal production in the Western region involves surface mining methods, while in the Eastern and Interior regions, underground mining accounts for roughly 60% of the total coal production.

In general, inactive coal mines are not considered as technically promising for disposal as active mines. Unreclaimed inactive and depleted surface mines usually consist of the final strip pit (which is often filled with water) and a series of ridges of overburden, leaving little available capacity for sludge placement. Reclaimed surface mines by definition do not have any capacity for FGD sludge disposal. Old and inactive underground coal mines are often caved, with remaining voids being difficult to locate and utilize for sludge placement.

On the other hand, FGD sludge disposal in active coal mines is technically promising on several counts. The quantity of sludge produced generally amounts to less than 50% of the weight of the coal burned; thus, there should be sufficient capacity for FGD sludge from a power plant to be returned to the active coal mine supplying the plant. Also, there is an existing network of transfer and handling equipment for the transport of coal from a mine to a power plant, and this network might be modified and expanded for use in transport of the sludge.

Surface coal mines in the Interior and Western regions appear to be the most technically promising because of their individual capacity and the relative ease of sludge placement within the context of the commonly employed area mining operation. Eastern surface coal mines are considered less promising because of their lower production capacity and the prevalent contour mining method which makes sludge placement more difficult. Of the underground coal mines, Eastern and Interior conventional room and pillar mines are the most technically promising. There are few underground mines in the Western regions (and these are of limited capacity). Because of roof caving, underground longwall mines and room and pillar mines practicing pillar robbing have limited capacity, and it will be difficult to locate remaining voids.

b. Metal and Nonmetal Mines

The two principal types of mineral mines are underground and open pit. Most metallic and nonmetallic mineral mines are open pit (or quarry). However, there are a significant number of underground mines producing limestone, gypsum, salt, copper, iron ore, lead, uranium, and zinc. The principal methods of underground mining are room and pillar, caving, and cut and fill (and its variation).

While there are countless inactive and abandoned underground mines, these are not usually promising for sludge disposal. Most of them involved mining methods employing caving, leaving limited capacity for sludge. Many are currently inactive for market reasons and may be reopened as market conditions dictate. Only the significant void left from past lead-zinc mining operations appears viable for sludge disposal, as high extraction percentages (>70%) were achieved by room and pillar methods, and future lead-zinc supplies would not be greatly affected by sludge disposal.

Of the active metal and nonmetallic mineral mines, underground room and pillar, lead-zinc, and limestone mines show the greatest promise for sludge disposal. Currently, there are more than a dozen active lead-zinc mines producing over 100,000 tons of ore annually and about 30 underground room and pillar limestone mines producing over 300,000 tons of limestone per year. Limestone mines are of particular interest, since all nonregenerable systems involve the use of limestone either directly or indirectly and a transportation network may already exist between limestone mines and FGD systems. However, where a large fraction of a limestone mine's production is used to supply FGD systems, it may not be able to dispose of all the sludge produced because the volume of dewatered, ash-free sludge (at 50% solids) is many times greater than that of the limestone used.

Other types of active underground mines are considered to be less promising due either to the value of the remaining unextracted ore that would be inaccessible after sludge disposal or due to the limited capacity and difficulty of sludge placement. Active open pit mines would not provide good disposal sites because the nature of the mining operation requires maintenance of the entire excavated area for downdip access to reserves.

2. Environmental Assessment

Based upon the screening of the mining industry, the methods of disposal available, and the overriding operational constraints in disposal, the following general mine options were selected for assessment:

Mineral	Mining Method	Region	Disposal Method	Sludge Form
Coal	Surface	Eastern, Interior, and Western	Truck Dumping Into Pit	Moist Filter Cake
Coal	Underground Room and Pillar	Eastern, Interior	Hydraulic Stowing	Thickened Slurry
	Longwall	Eastern, Interior	Pneumatic Stowing	Moist Filter Cake
Lead-Zinc	Underground	Interior	Hydraulic Stowing	Thickened Slurry
Limestone	Underground	Interior	Truck Dumping	Moist Filter Cake

The impacts of sludge disposal were assessed based upon a range of average mine conditions and range of untreated sludge characteristics common to each region. Methods for mitigating impacts were then assessed, taking into consideration factors such as sludge treatment, modification of disposal operations, control of site selection, and leachate collection and treatment.

a. Physical Impacts of Untreated Sludge

In the disposal of untreated sludge in mines the physical impacts of principal concern are: uncontrolled flow or seepage of sludge during disposal operations, consolidation of sludge deep-layered in surface mine pits, and the potential for liquefaction of sludge after disposal has been completed.

In order not to overly disrupt mining operations it is important in surface mine disposal that the sludge be relatively dry so that it can be easily handled and have minimal tendency to flow. However, while simple dewatering (by thickening and filtration or centrifugation) may produce a relatively dry sludge, the material may be near enough to its liquid limit that when rewetted slightly or stressed it may liquefy and flow. In addition, liquefaction could be caused by dumping overburden on sludge layered in the pit, by vibrations from nearby mining operations, or seismic disturbances.

In underground mines, liquefaction would be of principal importance where bulkheads are not employed to retain the sludge. Bulkheads would be part of a system employing hydraulic stowing but would not normally be included where pneumatic or dry stowing is employed.

Consolidation of sludge is of prime importance in surface mines where deep layers of sludges (greater than 5-10 feet) are created, particularly where the overburden is relatively shallow. The significance of consolidation depends on the time required for most of the settlement to occur and the ultimate proposed use of reclaimed strip mine land.

Both consolidation and liquefaction potential will importantly depend upon the properties of the sludge as well as the manner of sludge placement and loading on the sludge. As of the writing of this report there is no definitive data available on the properties of sludge relative to these effects.

b. Effects of Untreated Sludge on Water Quality

Most mines are wet, and it can be assumed that groundwater overlying the mined area will eventually flow into the mined area and saturate any FGD sludge deposit. Sludges disposed in surface mines are subjected to groundwater flowing through unconsolidated sediment and broken rock overburden. Underground mines receive groundwater flowing through cracks, fissures, and faults in overlying (and underlying) strata into the mined area. Under most mining conditions, FGD sludge is expected to be saturated unless measures are taken to isolate the sludge either by diverting groundwater or placing the sludge above the water table.

Groundwater moving through disposed sludge picks up soluble chemical species. According to leachate studies of FGD sludge, there is a first flush of soluble species from the liquor associated with the sludge lasting one or two pore volumes, with most species dropping to near their equilibrium concentrations after a displacement of about 10-30 pore volumes. Because of the extremely long time it takes for sludge to pass one pore volume of leachate through its matrix, leachate concentrations close to those of the original sludge liquor would be expected to prevail for hundreds to thousands of years. Significance of the impact of the leachate on groundwater will, of course, depend importantly on the total quantity of the constituents leached as well as its concentration. To some degree, leachate concentrations will be affected by the composition of the infiltrating water. In most cases, though, acidity levels per se in mine waters should have little effect on leachate concentrations, since few mines have drainage of pH less than 4, and accelerated leaching and elutriate tests at pH's of 4 and 7 show little difference in leachate concentrations (2).

Chlorides and sulfates are the major soluble species in sludge, and in most cases, TDS in the leachate plume would be expected to exceed recommended drinking water standards. Other species such as cadmium, mercury, and zinc would also be expected to be substantially raised in waters receiving sludge leachate; however, TDS levels should "red flag" contamination.

Little attenuation of soluble species is expected for most mine disposal situations. In most cases, the sludge would rest on rock strata in a layer below (and possibly partially mixed with) broken rock overburden, and there would generally be little or no direct contact of sludge or its leachate with soil. Therefore, adsorption of leachate constituents will not be significant in the immediate vicinity of the mine, and precipitation is the only feasible attenuation mechanism in most cases. Aluminum, beryllium, cadmium, copper, cobalt, iron, lead, manganese, mercury, molybdenum, nickel, and zinc may be partially precipitated under neutral to alkaline conditions. If limestone overburden is present, carbonate salts may form with cadmium, calcium, copper, iron, lead, and zinc. Insignificant attenuation of arsenic, boron, selenium, and chromium is expected. No attenuation of sodium, chloride, or sulfate would be expected.

Leachate from the sludge layer is accessible to surface water by two pathways: (1) mine sump pump-out, which contains a mixture of groundwater, sludge leachate, and surface runoff and (2) groundwater recharge of downgradient surface waters. The effect is obviously a function of the dilution factor of the receiving stream and its baseline water quality. In some cases, sludge leachate would be no worse (and conceivably better) than existing mine drainage, at least with regard to acidity levels and TDS, and leachate discharges to rivers polluted upstream by mining operations may not cause any appreciable impact on instream chemical concentrations. However, leachate discharges to pristine small streams may show significant water quality impact. Cadmium, mercury, and zinc in particular may be increased to above fresh water aquatic life criteria. From a biological standpoint, TDS in general and these three heavy metals would provide cause for concern in small pristine receiving streams. In addition to the direct toxicity problems of the estimated increments in these metals, the potential problems of accumulation and synergism would also exist in larger streams. Mercury and cadmium are persistent cumulative toxicants and the toxicity of the latter can be increased by zinc.

TOS (total oxidizable sulfur = sulfite + bisulfite) in leachate may also present a toxicity potential of concern, both in terms of the direct toxicity of the TOS itself and for its COD. Groundwaters tend to be anaerobic, and TOS could persist to receiving streams. Since little data are available on TOS in sludge leachates, TOS toxicity can only be identified at this time as a potential problem.

c. Control Techniques to Minimize Adverse Impacts

The control techniques available for minimizing adverse impacts include:

- sludge processing or treatment;
- control of disposal method;
- collection and treatment of sludge leachate or runoffs; and
- control of site selection.

Sludge treatment by chemical fixation techniques should enhance physical properties and thereby ensure minimal operational and physical impacts, although well-filtered sludge (possibly admixed with ash) may, in many cases, be adequate to avoid most adverse operational and physical impacts. A treated sludge would also reduce mobilization of pollutants through reduction in the sludge permeability, decreased sludge contact area, and possibly reduction in the solubility of potential pollutants.

Adjusting the disposal operations to isolate the sludge from the groundwater would improve environmental impacts. If in surface mines, part of the rock overburden were deposited in the pit to a depth above the groundwater table prior to disposal of the sludge, then the rate of leachage generation would be lessened. However, such an operation may be technically impractical or economically unattractive. In underground mines, disposal between strata of low transmissivity (a function of permeability and hydraulic gradient) would limit the access of groundwater to the sludge deposit and thereby limit leachate production.

Collection and treatment of sludge leachate does not appear to be a viable alternative for controlling environmental impacts. Groundwater collection requires extensive pumping wells or infiltration galleries, and the chlorides and sulfates collected in the leachate cannot be readily treated by existing wastewater processes.

The best control technique may be adequate evaluation and selection of the optimum site based upon the geologic conditions favorable to disposal and the characteristics of the sludge. Factors to be considered include: permeabilities of adjacent strata, hydraulic gradient of groundwaters through the mined area, seasonal location of the water table, type of pyrite coal and resulting acid drainage formation, buffering capacity of background groundwater, distance and pathways to downgradient receiving surface waters, and potential for attenuation of dissolved species.

d. Potential Benefits from Sludge Disposal

Neutralization of Acid Mine Drainage

All coal mines have potential for the formation of acid mine drainage as pyrite is exposed to air and water. A surface mine which is reclaimed concurrent with mining has less potential for acid drainage formation than one which is not immediately reclaimed. An underground room and pillar mine has the potential for continuously exposing pyrite to air and humidity, thereby allowing the worst acid mine drainage conditions to develop. An underground longwall mine, through controlled caving of the roof and pillar extraction, minimizes pyrite exposure and acid drainage formation. Disposal of FGD sludge could limit future acid drainage formation by sealing pyrite from air exposure.

Where there is presence of limestone in a surface or underground mine's overburden, neutralization of the acid mine drainage occurs. Similarly, FGD sludge has some ability to neutralize acid drainage. Calcium carbonate in the sludge would be expected to be the principal neutralization agent, since there is usually very little residual calcium oxide or calcium hydroxide. However, disposing of untreated sludge containing sulfite in very acidic waters may result in off-gassing of SO_2 which could prohibit such operations.

Subsidence Control

Subsidence may occur in underground mines when the seam extraction panel is large enough to induce the mine roof to fail and collapse into the mine void. In room and pillar mining, pillars are left in place to provide roof support. However, after a room and pillar mine is abandoned, natural deterioration of the pillars may weaken them sufficiently to allow roof collapse. In longwall mining, controlled roof collapse is a part of the mining operation, and subsidence is expected to occur within several days of ore extraction.

Experience with hydraulic and pneumatic stowing of coal refuse and sandfill in conjunction with longwall mining has indicated lessening of subsidence from 90% of the seam thickness to 25-55%. FGD sludge is not expected to achieve the same degree of subsidence control, especially if it does not readily consolidate on placement.

In cases of long-term subsidence attributed to pillar deterioration, deposits of treated or untreated FGD sludge could partially seal the pillars from air exposure, groundwater seepage, and microorganisms. As a result, the reaction rates of chemical and biological pillar deterioration should be significantly lessened. However, the use of treated sludge in some manner either to line or replace pillars to allow additional coal extraction is not considered economically attractive.

Untreated Sludge as a Tailings Amendment

Tailings are highly variable in composition, as are FGD sludges. Tailings have been successfully revegetated for over fifteen years, usually using "soil amendments" such as limestone, sewage sludge, fly ash (where available), and, less often, soil itself. Materials used as soil amendments are chosen on a case-by-case basis to meet particular needs, but the potential for any material as a soil amendment depends upon its ability to alleviate any conditions that limit plant growth.

In general, FGD sludge appears somewhat useful in its potential for reducing acidity (unless it is acidic itself), reducing heat absorption and increasing moisture retention. It is doubtful if sludge could alleviate any problems with phytotoxins or salinity and may aggravate such problems in some cases. To prevent creating new problems, the sludge to be used must be screened for heavy metals, salinity, and acidity. But even an alkaline sludge with low salinity and heavy metals holds less promise as a soil amendment than either limestone or sewage sludge.

3. Technology Assessment

a. Handling and Transport

There are four basic modes of transport that can be used for moving sludge: slurry pipeline, barge, truck, and rail. Since all of these modes are technically feasible, the selection of the most appropriate mode or combination of modes must be made on the basis of a cost/benefit analysis, taking into account all operations involved (processing, transfer, transport, and disposal) and institutional constraints that may be imposed (e.g., regulations governing waste transport inter- and intra-state).

The overall practicality of pipeline transport of sludge will depend upon a number of factors relating to the pipeline requirements and the operation of the FGD process and the disposal system. Of particular importance are the water balances at the power plant and mine, and the specific sludge dewatering or treatment requirements, if any, prior to disposal. Special consideration in the design of pipelines would have to be given to slurry viscosity, slurry velocity, abrasion/corrosion resistance, freeze protection, and potential long-term scaling or hardening of sludge in the pipe. These factors along with the institutional constraints of long-distance pipelines will act to restrict the practical distance of slurry pipelines for mine disposal to mine mouth power plants involving transport distances no more than a few miles.

Hauling sludge by rail is an attractive prospect, since most large power plants receive coal by rail; however, the sludge would need to be a moist filter cake or treated material. New facilities would be required at both the power plant and mine for storing, handling, loading, and unloading the sludge, all of which can be accomplished using existing, available technology (for a moist filter cake or processed material).

Truck transport and disposal of sludge is now used by utilities. Recent experience at a number of power plants indicates that untreated sludge should be at least the consistency of a moist filter cake with little tendency to liquefy, particularly if rear-dump trucks are used. Slurries or partially dewatered materials are difficult to load and dump and could leak liquor during transport, necessitating special trucks. Loading of a relatively dry material can be readily accomplished using a combination of conveyors and hoppers, front-end loaders, or bucket cranes. Special provisions may be required to prevent freezing of the sludge or excessive rewetting due to rainfall. It may also be necessary to provide for rail car washing at the mine site (including a system to collect and treat the runoff).

Where utilites receive coal by barge, barging of wastes would be a logical alternative to overland transport. While use of coal barges is possible, a barging system dedicated to sludge transport would provide greater flexibility, eliminate tying up coal deliveries, and minimize intermediate sludge storage. While barges could conceivably be used to handle thickener underflow, dry filter cake or treated material would result in fewer unloading problems.

b. Disposal Methods

Strip Mines

Disposal of filter cake or treated sludge in a surface mine would be most easily accomplished with rear-dump trucks, whether the sludge were returned to the pit prior to or along with overburden or were dumped between mounds of replaced overburden. Unless truck haulback methods were used for returning overburden, any operation other than simply dumping the sludge in the mined-out pit prior to the return of overburden would require additional road construction and a corresponding increase in disposal costs.

It would probably not be possible to use coal haulage vehicles, since sludge loading and dumping would increase truck cycle times and reduce productivity. Also, many newer trucks are large (80-100 tons) bottom-dump, aluminum-bodied trucks not amenable to maneuvering in coal mine pits, particularly on sludge layers.

Underground Mines

There are three approaches for disposal of wastes in underground mines: pneumatic backfilling, hydraulic backfilling (or flushing), and mechanical stowing.

There has only been limited experience with pneumatic backfilling of materials in U. S. mines, although there has been considerable work done in European coal mines, primarily with fly ash. In room and pillar mines, pneumatic backfilling would be accomplished by blind injection. In longwall mines it could be used to place sludge in the gob area as a part of the normal operation prior to roof collapse. However, if the sludge is too moist, it may clog conventional equipment, even when admixed with ash or tailings; and the presence of fly ash may cause excessive abrasion. On the other hand, the very fine fraction of the sludge, when sufficiently dried, may create dust problems not uncommon in pneumatic stowing operations.

There has been considerably more experience with hydraulic backfilling of ash and coarse tailings. Hydraulic backfilling could be accomplished either by controlled or blind injection. Unless sufficient slope exists, bulkheading will be required, particularly where sludge is introduced through boreholes in the mine roof. Depending upon viscosity, slurries up to 50-60% solids may be hydraulically stowed; however, 40% solids probably represents a reasonable upper limit. Hydraulic backfill of some treated sludges may require underground piping rather than introduction through roof boreholes. With hydraulic backfilling it may be necessary to collect any drainage or pump out decanted liquor for controlled discharge or treatment. Where dry sludge is reslurried at the mine, collected drainage may be recycled for slurrying the sludge.

Mechanical stowing can be used in any underground room and pillar mine using existing types of equipment and conveyance systems. In most mines, mechanical stowing would involve a labor-intensive, rather inefficient operation. In hillside limestone mines, though, mechanical stowing by truck dumping would be the preferred method of disposal, since these mines are readily accessible. However, this type of operation would limit the space utilization.

c. Monitoring

The measurement of physical, chemical, and biological changes that occur in the region of a disposal site is required to determine the fate and effects of the sludge. Monitoring of the site will be required prior to, during, and after disposal. It is particularly important that background data on site conditions (e.g., surface water, groundwater, geology, climate) be gathered for a period of at least one year prior to disposal to establish seasonal fluctuations and that a control site be monitored, if possible, during and after disposal. The particular chemical species to be followed will depend upon background groundwater levels and sludge characteristics, but general parameters that may be useful in detecting influx of leachate into groundwaters would be sodium, chloride, sulfate, and TDS. These are least attenuated by soil or rock.

Because continuous monitoring is not required and such monitoring devices are of limited availability, the monitoring program should be based on grab samples from groundwater wells. These need to be located within the disposal area as well as up and downgradient. Core samples will also be needed to assess physical and chemical changes in the sludge.

The frequency of sampling will vary for different disposal operations and will undoubtedly need to be adjusted according to observed effects. The initial sampling frequency should be based upon expected permeability and groundwater flow rates.

4. Regulatory Environment

a. Federal

Four areas of federal laws and statutes have been evaluated with regard to their adequacy for protecting the environment: waste disposal, transportation, water quality, and health and safety. Selected regulations issued by agencies in order to implement and enforce provisions of the relevant statutes were examined; however, regulations pursuant to the major transportation acts and the Occupational Safety and Health Act of 1970 were not included due to their extensive technical detail and numbers. The regulatory assessment was conducted from a legal perspective only, focusing on identification and characterization of relevant federal legislation, coverage provided by related laws and regulations, and characterization of administrative authority.

The following eighteen current federal statutes and regulations were reviewed:

- Waste Disposal
  - Solid Waste Disposal Act of 1965
  - EPA Guidelines for the Land Disposal of Solid Wastes
  - Resource Conservation and Recovery Act of 1976
- Transportation
  - Hazardous Materials Transportation Act
  - Transportation of Explosives Act
  - Hazardous Cargo Act
  - Ports and Waterways Safety Act of 1972
- Water
  - Federal Water Pollution Control Act Amendments of 1972
  - Safe Drinking Water Act
  - Dam Safety Act of 1972
- Health and Safety
  - Federal Metal and Nonmetallic Mine Safety Act

Health and Safety Standards for Metal and Nonmetallic Underground
  Mines and Proposed Amendments
Federal Coal Mine Health and Safety Act of 1969
Health Standards for Underground Coal Mines
Safety Standards for Underground Coal Mines
Health Standards for Coal Mine Surface Work Areas
Safety Standards for Surface Coal Mines and Surface Work Areas
  of Underground Coal Mines
Occupational Safety and Health Act of 1970

With the passage of the Resource Conservation and Recovery Act (RCRA) in October 1976, coverage provided by federal legislation should be extended to encompass all aspects of the disposal of FGD waste solids. Although regulations specifically addressing the disposal of FGD sludge have not yet been issued under the RCRA, it is expected to be the lead legislation regulating FGD sludge disposal.

In terms of overall solid and hazardous waste management, the RCRA provides for comprehensive regulatory authority at the federal level and an institutional framework for planning and regulatory implementation at the state level. Together with the Federal Water Pollution Control Act Amendments (FWPCA) and the Safe Drinking Water Act (SDWA), which now provide authority to regulate some aspects of underground discharges from wastes, the RCRA should provide adequate legal protection for both groundwater and surface waters. Under the RCRA, the FWPCA, and several of the health and safety statutes, FGD wastes will be subject to specific federal standards and criteria including:

- characterization of wastes (as hazardous or nonhazardous);
- point-source effluent guideline limitations (as influenced by the water quality of receiving streams);
- health standards pertaining to dust and airborne contaminants; and
- safety standards pertaining to refuse piles and impounding structures, roof support, and ventilation.

However, existing health and safety standards do not specifically address FGD sludge, and new legislation and/or modifications of existing standards may be required. Furthermore, appropriate administrative authority for regulatory promulgation and enforcement of health and safety standards need study and clarification. Any changes should be determined following a thorough technical assessment of the adequacy and applicability of existing standards to FGD waste disposal operations.

Existing laws and regulations, though, do appear adequate to cover transportation of FGD sludge. Transport of similar materials by modes of transportation under consideration for FGD sludge is a frequent and familiar practice of commerce, and existing transportation regulations in combination with the other legislation discussed above should provide adequate legal protection for the environment.

b. State

At the state level there are laws and regulations which either enhance existing federal laws and regulations or fill gaps in these regulations. Laws governing mining activities (i.e., reclamation, sealing, subsidence control, and acid mine drainage) and permit regulations for wastewater effluent, mine drainage, and solid waste disposal sites are generally covered at the state level.

In assessing state regulations, Pennsylvania was selected as a model state. Pennsylvania is an industrialized state with extensive mining operations and a number of utilities planning (or operating) FGD systems. The Department of Environmental Resources (DER) currently has lead responsibility for regulating sludge disposal in mines. The primary regulating statutes are administered by the Bureau of Land Protection and Reclamation, the Bureau of Water Quality Management, and the Bureau of Mine and Occupational Safety. The regulating statutes do not specifically address FGD disposal in mines; however, collectively the statutes can be interpreted as providing coverage for all aspects of sludge disposal.

In order to ensure orderly and environmentally sound disposal of FGD sludge, the DER is considering regulatory amendments to existing statutes. Some amendments regarding mine disposal may be clarified by a pilot field program recently undertaken under an EPA grant to evaluate sludge disposal in underground mines.

C. OCEAN DISPOSAL

1. Environmental Assessment

There is a basic distinction between shallow ocean (continental shelf) and deep ocean (off-shelf) environments. The upper levels of the water column in both these environments are contiguous and are treated as a unified environment. However, the lower water columns and sea bed of the continental shelf and deep ocean are distinct. The former is biologically productive and changeable, affording habitat for resources of importance to man, while the latter is stable, diverse, and of limited value in terms of living resource exploitation.

The "baseline" ocean dumping scenario chosen for analysis involves the use of conventional bottom-dump barges on the continental shelf. This would be the quickest, cheapest, preferred method in the absence of regulatory constraints. Thus, impacts are discussed below in terms of this mode of operation. Subsequent discussion focuses on major alternatives to this mode, including:

- dispersed dumping on the continental shelf;
- conventional dumping off the continental shelf (deep ocean);
- dispersed dumping off the continental shelf; and
- concentrated dumping of treated sludges.

a. Physical Transport

The physical fates of sludge of three different consistencies have been evaluated. These types are: dewatered (untreated), slurry (dispersed), and treated (brick-like).

At some solid content (perhaps on the order of 70% for some materials) dewatered, untreated sludge probably hangs together and falls through the water as a cohesive mass. Simple lab experiments and preliminary modeling results indicate that more than 95% of the dumped material will reach the bottom intact after rapid descent and remain as a heap on the bottom. Continuous utilization of the same site would result in the accumulation of significant amounts of dumped material.

Sludge slurries which have been considerably diluted or which simply have a low solids content will very likely disperse widely and sink slowly. Within a few minutes, FGD sludge slurries would be expected to be distributed throughout a water column several hundred feet in depth. The initial dilution achievable by available equipment is expected to range between 5×10^2 and 1×10^4.

Preliminary findings indicate that treated, brick-like sludge would sink quickly and remain intact on the bottom for an indeterminate period of time. Uncertainty surrounding the dissolution rate of such material needs to be resolved.

b. Environmental Impact Potential

Four principal categories of potential impacts for FGD sludge disposal in the ocean environment are discussed below. These are:

- impacts on benthic sedimentation;
- impacts of sludge suspended in the water column;
- impacts of sulfite-rich sludge; and
- trace contaminant impacts.

The chosen order of presentation does not necessarily reflect the relative significance of these several impact potentials.

Benthic Sedimentation

The benthic environment in the vicinity of dump sites would be characterized by substrates substantially or entirely composed of sludge. Such conditions would have serious impact potential. Benthic ecologists generally regard the coarse-grained substrate (e.g., coarse sand) as most conducive to the establishment of rich, diverse marine benthic macrofaunal assemblages. Sediments of finer composition, especially if relatively uncompacted, provide the least stable and most limiting type of habitat. In addition to the physical character of the sludge, its relative lack of nutrient content may serve as a further limitation upon benthic faunal community establishment.

Sludge Suspended in the Water Column

Many of the dominant finfish of the continental shelf dump sites may be expected to exhibit intermediate sensitivity to suspended sediments. In quantitative terms this sensitivity may be defined as experiencing 10% mortality during 24-hour exposure to suspended sediment concentrations between 1,000 and 10,000 mg/liter. Such concentrations would be expected upon initial dilution throughout the dump site water column, but duration of organism exposure is expected to be brief in the upper and mesopelagic zones.

The extent to which other contaminants (including sulfite and heavy metal residues) are part of the dumped sludge is another important aspect of impact potential. Once within the stomach of a fish, particles are exposed to acidic conditions capable of stripping absorbed contaminants and making those contaminants available for damage or concentration within the organism or elsewhere in the food web. Thus, certain major contaminant impact potentials may be relatively independent of the extent to which *water column* concentrations of sulfite or trace metals might be increased by dumping activities. These types of impacts could be important over the long term at dump sites to such benthic finfish as cod and flounder, whose feeding habits involve sediment suspension and ingestion.

Sulfite-Rich Sludge

The impact of the introduction of sulfite into the ocean environment as consequence of FGD sludge disposal is of interest for two reasons. First, sulfite has a measurable toxicity; and second, it will react with dissolved oxygen, leading to a depletion of dissolved oxygen.

If the sludge is diluted by a factor of 500 in the course of being dumped, the resultant concentration of sulfite in the stomach of disposal area fish might be on the order of 0.006 M. This concentration is roughly six times the median 50% lethal concentration for fish at pH 6 (0.001 M) observed under laboratory conditions (8). Sulfite toxicity has been demonstrated to be pH dependent, increasing with decreasing pH. Thus, a concentration of 0.006 M sulfite in the stomach of finfish, where pH levels would be 1 or 2, may have especially serious impacts. However, more data needs to be obtained concerning organism uptake of suspended particles of FGD sludge during the short-term exposures that would be characteristic of ocean dumping conditions before the real impact potential of sulfite-rich sludges regarding toxicity can be accurately quantified.

If the FGD sludge solids would dissolve instantaneously upon being diluted and dumped, and if the oxidation in real seawater would proceed as rapidly as uncatalyzed laboratory experiments proceeded, one would expect to find severe reductions in dissolved oxygen in the vicinity of the dump. However, calcium sulfite is very insoluble and it is unlikely that complete dissolution would occur in one or a few minutes. It is likely that solids dissolution rather than oxidation would be the limiting step in the dissolution/oxidation sequence.

Trace Contaminant

The anticipated initial dilution of sludge liquor by a factor of 500 could result in concentrations of five trace metals approaching or in excess of the "minimum risk" levels recommended by the National Academy of Sciences (NAS) (9). In decreasing order of apparent impact potential, these metals are: mercury, zinc, selenium, cadmium, and nickel. Four of these five (excepting selenium) are included in the elements of principal concern identified by Ketchum et al. (10).

The reported range of trace contaminant levels in the solid phase of FGD sludges encompasses considerably higher concentrations than found in the sample sludge liquors. As with the liquors, values in the high range have been obtained from sludges containing fly ash. As in the case of sulfite, the impact potential of trace contaminants bound or adsorbed to solid fractions of the sludge will be dependent upon critical variables such as dissolution rate and particle uptake by free-swimming organisms. Too little is known of these types of interactions over the short term to allow for a feasible prediction of quantitative impacts.

C. Environmental Impact of Applicable Control Options

Restrictions on Sludge Composition

The impacts of benthic sedimentation, as discussed above, would not be affected to any significant degree by restricting types of untreated sludges disposed of on the continental shelf by bottom-dump barges. Likewise, the impacts of suspended sludge in the water column would not be affected from the gross standpoint of organisms' sensitivity to sediments in general. However, two subsets of the suspended sediment impacts, the impacts of sulfite and associated trace contaminants, could be significantly mitigated by restricting the types of sludges disposed of at sea.

Disposal by Dispersion

If FGD sludge slurries were pumped overboard in a manner sufficient to achieve instantaneous dilution on the order of 5,000 to 10,000, three of the four impact potentials discussed above would be substantially mitigated. Sulfite impacts would remain of potential significance in the dispersed disposal option.

Concentrated Bottom Disposal

For purposes of this discussion, concentrated bottom disposal is presumed to include chemical treatment of FGD sludge resulting in a cement- or brick-like waste product. It appears that all four of the principal impact potentials discussed above would be substantially mitigated by this control option. Of course, overriding this and all other considerations of this control option is the question of dissolution. If the lifetime of the material in concentrated form is relatively brief, two of the advantages of this option would be removed. The trace contaminants within the treated sludge would become available upon dissolution and still might be problematic. Provided that questions concerning the dissolution of concentrated, treated sludge can be resolved, this option appears to offer considerable promise.

Chemical Treatment

With the exception of concentrated disposal of brick-like treated material, chemical treatment appears to offer few, if any, advantages over the traditional bottom-dump disposal of untreated FGD sludge. The sulfite impacts discussed above might be mitigated to considerable degree by chemical treatment, but the impacts of benthic sedimentation and suspended sludge in the water column would be comparable to those associated with typical untreated material. Trace contaminant impact potential could be equal to, or possibly greater with soil-like chemically treated sludge containing fly ash, than with untreated material. The potential impacts from brick-like treated material are expected to be less but remain unquantified.

Deep Ocean Dumping

In general, the short-term effects of conventional dumping of FGD sludge in the upper water column (pelagic zones) of the deep ocean would be similar to effects described above for the continental shelf. The major differences between deep ocean and on-shelf disposal emerge in consideration of long-term benthic and food web impacts.

The wider dispersion that would be achieved by disposal in depths of several thousand feet would preclude many of the adverse impacts of benthic sedimentation associated with shallower on-shelf disposal. The differences between deep ocean and on-shelf disposal regarding suspended sediment and sulfite impacts appear relatively minor.

The impacts of dissolved trace contaminants in sludge liquors would be similar to those discussed above in conjunction with on-shelf disposal. However, two characteristics of the deep ocean dumping environment tend to mitigate trace contaminant impact potential. First, deep ocean sediments appear to be a natural sink, exhibiting considerably higher concentrations of potential contaminants than near-shore areas. Second, and more important, the lack of opportunity for contact between contaminants residing in the deep ocean benthos and food webs of importance to man would largely eliminate the risk of pollution episodes affecting human populations. The trade-off between impacting the relatively stable but areally extensive deep ocean communities would have to be weighed against these advantages.

Disposing of only sulfate-rich sludges in the deep ocean would serve to mitigate one of the remaining principal impact potentials, i.e., sulfite toxicity. Overall, deep ocean disposal of sulfate-based wastes by conventional means appear to be a relatively viable option on environmental grounds.

Disposal by dispersion sufficient to achieve instantaneous dilution on the order of 5,000 to 10,000 also appears to be a relatively viable option from an environmental standpoint. These levels of initial dilution would mitigate suspended sediment and trace contaminant impacts, probably reducing them to insignificant levels. Potential problems of sulfite toxicity and/or oxygen demand in the upper water column would be mitigated but perhaps not resolved by deep ocean dispersal.

Disposing of treated brick-like FGD sludge in the deep ocean is probably the most desirable of all options considered from an environmental standpoint. All of the major impacts discussed above would be substantially mitigated by this combination of controls. The disposal of chemically treated, soil-like FGD sludges in the deep ocean could also mitigate sulfite impact potentials. Combined with dispersion, this would probably be a relatively attractive environmental alternative. However, the combination of treatment and deep ocean disposal may not be economically attractive.

2. Technology Assessment

Assessment of the technology available for the dumping of FGD sludge in the ocean focuses on three areas: transportation, navigation, and surveillance and monitoring. For this assessment, investigation in each area determined whether technological means for successful dumping exists or could be developed within the present state-of-the-art.

a. Transportation

Transportation from the shoreline to offshore dump sites (either on the continental shelf or off) could be accomplished using either surface vessels (self-propelled or tug/barge combination) or pipeline.

The technology for appropriate underwater pipeline construction falls into three categories: bottom pull, floating pipe, and lay barge pipeline positioning. Lay barge techniques have been used to install underwater pipelines of 30-inch diameter for distances over 100 miles.

The costs of offshore pipelines generally vary with length of the line, depth, pipe size, ocean terrain, and materials to be transported. The greatest single cost factor in such pipelines is the installation cost, which generally runs more than 50% of the total investment. Maintenance is usually the biggest cost factor in the operation of such pipelines.

Surface craft adequate for offshore disposal purposes exist and are in use today. There are two large-capacity bottom-dump type barges currently built in the United States (the largest in the world) which carry American Bureau of Shipping ocean-going classification—a 3,000-cubic yard (4,050-ton) barge and a 4,000-cubic yard (5,000-ton) barge. Such barges would have roughly the capacity required for sludge disposal operations.

Self-propelled hopper-type ships are also currently in use for waste disposal. The basic configuration of these types of vessels would resemble the hopper-type dredges owned and operated by the U.S. Army Corps of Engineers. The capacity of these hopper dredges varies from a low of 720 cubic yards to a high of 8,277 cubic yards; however, European dredges have now reached 15,000 cubic yards capacity.

Better (specially designed) equipment is feasible. Newer designs may be required to control the rate of release of sludge, particularly where high dilution factors are required. However, under almost all conditions, disposal of slurried sludge would be economically impractical. The cost of transporting FGD slurries would be unattractive, and reslurry of dry or thickened sludge on board large disposal vessels would require impractically large pumping capacities.

A major cost consideration for surface craft involves the necessity to employ two or three crew shifts if the dump site is located outside a round trip range which can be covered in eight hours or less.

h. Navigation and Surveillance

To limit the impacts of sludge disposal, the location of dumping has to be controlled. There are two aspects to such control. The first deals with navigational accuracy available (or the ability to find any specified dump site with precision). The second deals with policing the operation to make certain that dumping takes place at the specified location (within the accuracy limits of the available navigation systems).

Adequate means of navigation are currently available to allow fixing the location of any particular dump to well within one mile with visual control and within 0.5 to 3.0 miles with Loran-A, an electronic navigation system currently in use along all coastlines of the United States, the Great Lakes, the Gulf of Alaska, the Hawaiian Islands, and Puerto Rico. The Loran-A navigation system is old and relatively expensive to maintain. It is to be phased out of operation over the next 7-10 year period. Recently, Loran-C, OMEGA, and NAVSAT have become available for use by commercial shipping. Loran-C now provides precision accuracies of ±0.25 to ±0.5 nautical miles without degradation at sunrise or sunset. System improvements now underway are expected to provide a 15-20 fold improvement in precision accuracies.

Precisional accuracies on the order discussed above are certainly adequate to the navigational requirements of pumping. However, for the purposes of surveying and site monitoring, it may be necessary to achieve even greater accuracies in some instances, e.g., for work with submersible vehicles. Sonar Transponder systems are available which allow a submersible to return to its exact previous position.

Surveillance of ocean dumping is currently accomplished by the U.S. Coast Guard (USCG) through a manned system of ship riders, and waterborne and airborne observers. Development of an automated Offshore Disposal Surveillance System (ODSS) is underway. The ODSS system will use a fully automatic Loran-C receiver, data logger, and recorder with a format on magnetic tape suitable for computer analysis by the USCG, if required.

ODSS may also be interlocked with dump release mechanisms, thus assuring accurate location of dumps. Such equipment could be required before permits are issued.

c. Monitoring

In this context, monitoring is distinguished from model verification research, although both activities require work at sea. Model verification work needs to be performed in order to provide the reliable capability of predicting plume dispersion in time and space. Once adequately accomplished, there will be no need for routinely duplicating the original work. Monitoring, on the other hand, requires the definition or establishment of an environmental baseline and routine resurveys to determine whether changes have taken place, the nature of the changes, and their trends.

A baseline survey of the magnitude required prior to sludge dumping could generally be expected to require up to 18 months to complete. One cruise alone might last one to three weeks. Trend assessments will be required at the FOD disposal site three to four times per year after disposal begins. Additional surveys of selected critical parameters may be necessary during periods of heavy dumping.

Standard oceanographic techniques exist for collection and analysis of water, sediment, and biotic samples. Special large-volume samplers and highly sensitive laboratory techniques have been developed to monitor trace constituents. However, the reliability of these techniques is such as to require caution to interpreting the results.

Currents can be determined directly and indirectly. Indirect measurements (e.g., drift cards or drift bottles) require long periods of observation and subjective interpretation but can be relatively inexpensive for each data point. Moored current meters (and other instruments) can provide long-term direct observations which are highly useful. However, reliability is still a problem, and fouling or other failures which degrade efficiency or render the data useless are issues with which to deal.

Bathymetric surveys can be accomplished with sufficient horizontal and vertical accuracy and precision to provide effective monitoring of a concentrated dump site.

Recent experience indicates that offshore ocean dumping site surveys that require one to two weeks of ship time to complete will require an additional three to four months for data evaluation, analysis, and reporting. A typical ocean survey program of this type costs in the range of $200,000 to $250,000 per cruise including preliminary conclusions and a summary data report.

3. The Regulatory Environment

The regulatory environment is discussed in terms of the current statutory base, administrative regulations, and agency attitudes.

The discussion of legislation highlights five aspects of the Marine Protection Research and Sanctuaries Act of 1972 (P.L. 92-532), the basis for all domestic regulation of ocean dumping. These are:

- statement of policy;
- mandatory considerations in the issuance of permits;
- penalties;
- preemption of other jurisdictions; and
- establishment of regulations.

Substantive revisions to the EPA Ocean Dumping Regulations are still pending as of this writing. The following four aspects of existing and pending regulations are focal points in this report:

- consideration of alternatives;
- prohibited materials;
- other factors limiting permissible concentrations; and
- monitoring requirements.

Agency attitudes were sampled by visits with administrative and technical support staff at EPA headquarters, Marine Water Quality Laboratories, and regional offices. In summary, the regulatory environment surrounding ocean dumping is not favorable to new dumping initiatives at this time. The phasing-out of existing dumping and alternatives to future dumping are receiving emphasis. In addition, unless proposed regulations are modified, Eastern sludges could be precluded from ocean dumping entirely on the basis of the cadmium content of the solid phase. Mercury limits are also specified but appear to be somewhat less of a potential constraint on FGD sludge disposal.

D. ECONOMICS OF CONCEPTUAL DISPOSAL SYSTEM DESIGNS

1. Basis for Design and Economics

Conceptual system designs and general capital and operating costs have been prepared for five ocean disposal and six mine disposal options. Costs are based upon 365,000 tons per year of dry sludge (including ash) from a 500-megawatt power plant burning typical Eastern coal (3.0% sulfur, 10.0% ash, and 0.85 lbs of coal/kwh). The sludge (with ash) is assumed to be available either as a dry filter cake (50% solids), a 35% solids slurry (thickener underflow), or as treated sludge. No costs have been included for sludge processing such as filtration, drying, fly ash addition, or treatment; however, where treated, brick-like sludge is handled, an estimate for excavation of treated sludge from stabilization ponds or impoundments has been included.

Capital costs are based upon 1978 completion of construction and include: installed equipment cost for the battery limits disposal system (transfer/handling/placement), engineering and contractors' fees, working capital, owner's expense, startup, and interest and escalation during construction. Not included in capital investment are extensive site preparation, land cost, auxiliary utilities, fees for permits, or, as previously indicated, sludge treatment equipment.

2. Coal Mine Disposal Economics

The conceptual systems include the disposal of both filter cake (admixed with ash) and treated sludge in onsite and offsite surface area coal mines, and the disposal of slurried, untreated sludge (with ash) in onsite and offsite underground coal mines. For onsite mines, either truck transport (filter cake and treated sludge) or pipeline (thickener underflow) are used for transport of the sludge. For offsite mines, rail haul of either treated sludge or filter cake is assumed. Preliminary estimates have shown truck haul and slurry pipeline to be impractical for long-distance sludge transport.

For untreated sludge (or treated, soil-like sludges) estimated disposal costs including transfer and intermediate storage range from $3.00-3.50 per dry ton for onsite disposal to $6.50-8.00 per dry ton for offsite disposal. Disposal of treated sludges requiring the use of stabilization ponds or impoundments increases costs by about $2.00-2.50 per ton to account for excavation of the ponds. These estimates do not include site monitoring costs, which are strongly a function of the hydrology, sludge characteristics, and parameters (species) measured. Sludge processing costs must also be added to these transfer/placement costs to determine overall disposal system economics.

3. Ocean Disposal

Conceptual system designs and associated costs have been developed for five ocean disposal options--two for on-shelf (25 nmi) and three for off-shelf (100 nmi) dumping. Estimates include on-shelf disposal of both untreated and treated, brick-like sludge; and off-shelf disposal of untreated filter cake, thickener underflow and treated, brick-like sludge. While disposal of untreated sludge on the shelf is not presently considered promising due to the potentially adverse environmental impacts, it has been included for comparative purposes.

It is assumed in preparing the conceptual system designs that the sludge is produced in an Eastern power plant with ready access to the ocean, i.e., facilities for berthing barges are available with sufficient area for installation of a sludge transfer/storage system. Costs have been developed for operations including tug/barge combinations and self-propelled ships. In all cases, the system costs utilizing self-propelled ships are less than for tug/barge combinations due to the lower capital investment (shorter cycle times for ships and, therefore, fewer ships required).

In summary, disposal of untreated filter cake (with ash) on the shelf is estimated to run $4.00-5.00 per dry ton of sludge. For treated sludge requiring stabilization ponds or impoundments, costs would be approximately $2.00-2.50 per dry ton to cover the cost of excavation of the sludge. Deep (off-shelf) ocean disposal of filter cake or treated sludge runs about $3.00-4.00 per dry ton more than shallow (on-shelf) ocean disposal. And disposal of thickener underflow in the deep ocean costs approximately $1.00 more per ton than filter cake disposal. As with mine disposal costs, these estimates do not include monitoring costs (which are not a direct function of the sludge quantity) or sludge processing costs.

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IV. CHARACTERISTICS OF FGD SLUDGES

A. CHEMICAL CHARACTERISTICS OF UNTREATED FGD SLUDGES

The chemical composition of the sludge produced by any given FGD process at any particular time depends upon a number of factors including the composition of the coal being burned, the type of boiler and its operating conditions, the method of particulate control employed, and the type of FGD system employed and the way in which it is operated. Because of the numerous variables involved, sludge composition can vary over extremely wide ranges. The following sections review ranges of chemical composition which might be encountered in FGD sludges. The results of sludge composition measurements that are presented have been assembled from a variety of sources and represent those available as of this writing. Principal sources of data have been the studies conducted by The Aerospace Corporation (Aerospace) and the United States Army Engineer Waterways Experiment Station (WES) for the Environmental Protection Agency (EPA). These programs, and others, are continuing and it is expected that additional data on sludge characteristics will be available in the near future.

The samples characterized in most studies usually consist of one or at most a few samples taken from different FGD systems on particular days. It must be stressed that the compositions of samples taken from any one of the systems could be quite different on different days. Similarly, the same type of FGD system installed on another boiler and run under a different set of operating conditions can produce a sludge with entirely different properties. Thus, the data cited should be viewed as illustrative of the effects of various phenomena which can influence sludge composition rather than as defining the composition of sludge produced by a particular process or process type.

1. Major Components in FGD Sludge Solids

The major solid components comprising FGD sludges include calcium-sulfur salts (usually calcium sulfite, calcium sulfate, or a mixture of the two) with varying amounts of calcium carbonate and fly ash. The ratio of calcium sulfite ($CaSO_3 \cdot 1/2\ H_2O$) to calcium sulfate (usually present as gypsum, $CaSO_4 \cdot 2H_2O$) can vary over an extremely wide range.

Table IV-1 contains examples of sludges which contained only very small amounts of calcium sulfate (Paddy's Run) and some which contained essentially no calcium sulfite (Mojave and Utah). Oxidation, and consequently the calcium sulfate-to-calcium sulfite ratio, is usually greater in systems burning low sulfur western coal. Less oxidation usually takes place in direct lime than in direct limestone systems. However, it is possible to promote oxidation in either of those systems to produce sludges with a high calcium sulfate/calcium sulfite ratio. The same is true for dual alkali systems. When high sulfur coal is burned and the boiler and FGD system are operated appropriately, the calcium-sulfur salts can consist primarily of calcium sulfite. However, if intentional oxidation is performed, gypsum can be the predominant calcium-sulfur salt.

Fly ash is the other major component which can vary over wide concentration ranges. In some systems, e.g. Paddy's Run, Mojave, or Scholz, fly ash is collected separately in electrostatic precipitators or mechanical collectors ahead of the FGD scrubber. Such fly ash collection is usually very efficient and little if any fly ash is found in the sludge. In other systems, the SO_2 scrubber also functions as a particulate control device and the collected fly ash can comprise from 20 to 60% of the FGD sludge solids. Even in installations where fly ash is collected separately, it can be admixed with ash-free sludge in an attempt to improve the handling properties of the sludge.

Varying amounts of unreacted limestone ($CaCO_3$) can be found in the sludges from direct limestone processes. Direct lime and dual alkali processes utilizing lime for regeneration usually operate with only small amounts of excess lime over that required for liquor regeneration. However, lime is often contaminated with some limestone which passes through the system unreacted and ends up in the sludge, and lime can also react with CO_2 for mixing small amounts of $CaCO_3$. Some dual alkali processes employ sodium carbonate softening to reduce dissolved calcium levels in order to minimize scrubber scaling. The softening reaction produces calcium carbonate, which leaves with the sludge.

Other calcium-sulfur salts have been reported in certain FGD sludges on the basis of X-ray diffraction measurements. They have been detected in only isolated cases and their presence needs to be confirmed by other

TABLE IV-1

MAJOR COMPONENTS IN FGD SLUDGE SOLIDS

Plant	Location	Process	Percent by Weight					Source (Ref)
			$CaSO_3 \cdot 1/2H_2O$	$CaSO_4 \cdot 2H_2O$	$CaCO_3$	Flyash	Other	
Shawnee	Eastern	Limestone	19–23	15–32	4–42	20–43		1
Shawnee	Eastern	Lime	50	6	3	41		1
Duquesne	Eastern	Lime	13	29	0.2	60	9.8% [illegible]	1
Paddy's Run	Eastern	Lime	94	2	0	4		2
Cholla	Western	Limestone	11	17	2.5	59	[illegible]	1
Mojave	Western	Limestone	2	95	0	3		2
Parma	Eastern	Dual Alkali	14	72[a]	0	7		3
Scholz	Eastern	Dual Alkali	65–90	5–25	2–10	nil		4
Utah	Western	Dual Alkali	0.2	82[b]	11	9		1
Montana	Western	Fly Ash	0–5	5–30	nil	40–70	5–30% $MgSO_4$	5

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[a] Portion ([illegible] of sludge) reportedly $CaSO_4 \cdot 1/2H_2O$

[b] Portion ([illegible] of sludge) reportedly $CaSO_4$

chemical tests. However, on the basis of known FGD system chemistry, the presence of those substances, regardless of what their exact identity is finally determined to be, should not significantly alter the general characteristics of FGD sludges as related to their disposal.

2. Trace Elements in FGD Sludges

A variety of trace elements find their way to FGD sludges from a number of sources. Coal itself contains a large number of trace elements present either in minerals occluded within the coal or as organometallic compounds (compounds of arsenic and selenium, in particular) distributed throughout the coal itself. The lime or limestone generally used as a reagent in FGD systems also contains mineral impurities which contribute trace elements to the sludge. And, depending on the quality of the process water used in the system, measurable amounts of trace elements can enter with it. However, there are few reported measurements of trace elements in process water and makeup chemicals.

The level of trace elements in the sludge depends primarily upon three factors: the level of various trace constituents in the coal relative to its sulfur content (and in FGD process additives); the amount of ash, if any, collected with or admixed with the sludge; and the efficiency of the scrubber system in capturing volatile trace constituents. Many of the elements are not highly volatile and will be retained in the ash (fly ash and bottom ash) matrix. The extent to which fly ash is a part of the sludge composition determines the presence of the least volatile elements in FGD sludge but has little impact on the presence of highly volatile elements. On the other hand, the concentrations of such highly volatile elements as arsenic, mercury, and selenium which appear in the sludge will depend upon the extent to which they are present in and released from the coal and, more importantly, the efficiency with which they are captured in the scrubber. Mercury and selenium are likely to be present in the flue gas as elemental vapors that might not be scrubbed efficiently.

Assuming that the limestone, lime, and process water makeup to the system are not contaminated with trace elements and that all highly volatile species are captured in the scrubber, then the FGD system would increase the concentration of trace elements proportionate to the coal weight lost upon combustion. Since the burning of one ton of coal produces 0.05-0.20 tons of dry scrubber sludge without fly ash (depending upon the sulfur content and SO_2 removal efficiency) and up to 0.4 tons of scrubber sludge with fly ash, it could be expected that trace element levels in the sludge could increase by a factor of 2X to 20X over those found in coal.

In addition to changes in concentration of trace constituents in sludge as compared to coal, there is also a change in the form and availability of these constituents. Important differences in trace element chemistry and availability between the original coal material and the FGD sludge are as follows:

Original Coal	FGD Sludge
Trace elements contained in highly insoluble mineral matrix and therefore inaccessible and immobile	Trace elements dispersed in potentially soluble $CaSO_4$ and $CaSO_3$ matrix and therefore eventually accessible
Undisturbed geological material compact, relatively non-porous with low leaching rates	Sludge composed of fine particles with finite permeability
Trace elements usually present as stable, insoluble organometallics, sulfides, or carbonates (6)	On combustion, trace element containing compounds are converted to oxides (in certain cases, elemental forms) which are more soluble and chemically reactive

A number of the important trace elements which have been found in FGD sludges containing up to 60% ash are listed in Table IV-2 along with the range of concentrations at which they have been detected in conjunction with measurements performed on from 5 to 9 samples. Also included are the median observed concentrations for the particular sets of samples studied and a comparative listing of ranges of trace metal levels which have been measured in a variety of coal samples.

The observed concentrations range over as much as two orders of magnitude which is a result, primarily, of the fact that the levels of trace elements in coal can vary by that same extent. The measured concentrations of a given element in the sludge samples studied generally fall within the same range as do typical concentrations in coal. That the trace element

TABLE IV-2

CONCENTRATIONS OF TRACE ELEMENTS IN FGD SLUDGES

Element	Concentration Ranges (ppm)	Median Concentration (ppm)[a]	Number of Observations	Range of Trace Elements Measured in Coal (ppm) (6)
Arsenic	3.4–63	33	9	3–60
Beryllium	0.62–11	3.2	8	0.08–20
Cadmium	0.7–350	4.0	9	–
Chromium	3.5–34	16	8	2.5–100
Copper	1.5–47	14	9	1–100
Lead	1.0–55	14	9	3–35
Manganese	11–120	63	5	–
Mercury	0.02–6.0	1	9	0.02–30
Nickel	6.7–27	17	5	–
Selenium	<0.2–19	7	9	0.5–30
Zinc	9.8–118	57	5	0.9–600

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[a] Values as reported.

Source: References (1) and (7).

concentrations in sludge is not observed is not known at the present time. However, only a few sludge measurements have been made, and in none of the cases was the coal analyzed for its trace element content.

3. Composition of Liquors Entrained Within FGD Sludges

The liquid phases of FGD sludges contain dissolved in them a wide variety of substances ranging from trace amounts of a variety of metals, some of which are toxic at low levels, to substantial amounts of commonly occurring ions like sodium, calcium, chloride, and sulfate. Because the substances dissolved in sludge liquors are more available to impact the environment quickly when the sludge is disposed of than are substances in sludge solids (and also because liquors are considerably easier to analyze than solids) the compositions of FGD sludge liquors have been studied in considerably more detail than have compositions of sludge solids. Drawing primarily from the studies at Aerospace and WES, the ranges of concentrations at which a number of substances have been detected in sludge liquors and elutriates have been tabulated in Table IV-3. Again, as was the case with the composition of FGD sludge solids, the concentration at which a substance was detected in the sludge liquor varied by a factor of 100 or more. The results of direct measurements and elutriate tests were combined in preparing Table IV-3 because the elutriate tests produced results which covered about the same range as did the direct measurements. Dilution accompanying the elutriate test could have been at most a factor of ten; lower concentrations were probably not observed because of the relatively large reservoirs of trace elements available for dissolution from the solids. Because for some substances the set of observed concentrations contains one value which is very much greater or very much less than the remaining observations which are grouped more closely together, the median value for each set of measurements is also included in Table IV-3 to provide an indication of what a "likely" concentration might be.

On the basis of both the median and maximum observed concentrations, antimony and arsenic concentrations seem to be higher in FGD sludge liquors produced from eastern coals. On the other hand, levels of boron and chloride appear higher in sludge liquors from western coals. It must be point out, however, that the variation in concentrations of a particular substance in

TABLE IV-3

LEVELS OF CHEMICAL SPECIES IN FGC SLUDGE LIQUORS AND ELUTRIATES

Species	Eastern Coals			Western Coals		
	Range in Liquor (ppm)	Median (ppm)	Total No. of Observations	Range in Liquor (ppm)	Median (ppm)	Total No. of Observations
Antimony	0.46–1.6	1.2	4	0.09–0.22	0.16	2
Arsenic	<0.004–1.8	0.027	15	<0.004–0.2	0.009	7
Beryllium	<0.0005–0.05	0.014	16	0.0006–0.14	0.013	7
Boron	41	41	1	8.0	8.0	1
Cadmium	0.004–0.1	0.023	11	0.011–0.044	0.032	7
Calcium	470–2,600	700	15	240–(>45,000)^b	720	6
Chromium	0.001–0.5	0.020	15	0.024–0.4	0.08	7
Cobalt	<0.002–0.1	0.35	3	0.1–0.17	0.14	2
Copper	0.002–0.4	0.015	15	0.002–0.6	0.23	7
Iron	0.02–0.1	0.026	5	0.42–8.1	4.3	2
Lead	0.002–0.55	0.12	15	0.0014–0.37	0.026	7
Manganese	<0.01–9.0	0.17	8	0.007–2.5	0.74	6
Mercury	0.0009–0.07	0.001	10	<0.01–0.07	<0.01	7
Molybdenum	5.3	5.3	1	0.91	0.91	1
Nickel	0.03–0.91	0.13	11	0.005–1.5	0.08	6
Selenium	<0.005–2.7	0.11	14	<0.001–2.2	0.14	7
Sodium	36–20,000^a	120	6	1,650–(>8,000)^a	—	2
Zinc	0.01–27	0.046	15	0.028–0.88	0.16	7
Chloride	470–5,000	2,300	9	1,700–43,000^b	—	2
Fluoride	1.4–70	3.2	9	0.7–3.0	1.5	3
Sulfate	720–30,000^a	2,100	13	2,100–18,500^a	3,700	7
TDS	2,500–70,000^a	7,000	—	5,000–95,000^b	12,000	3
pH	7.1–12.8	—		2.8–10.2	—	

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[a] Levels of soluble sodium salts in dual alkali sludge (filter cake) depend strongly on the degree of cake wash. The highest levels shown reflect single measurements on an unwashed dual alkali filter cake. (See text.)

[b] Levels of soluble chloride components in sludges are dependent upon the chloride-to-sulfur ratios in the coal. The highest levels shown are single measurements for a western limestone scrubbing system operating in a closed-loop using cooling tower blowdown for process makeup water.

Source: References (1) and (7).

sludge liquors from two plants burning one type of coal can be much greater than the relatively small difference which appears to be a function of coal type.

With regard to the trace elements present in FGD sludges, a comparison of Table IV-3 with Table IV-2 shows quite clearly that only a very small fraction of the total amount of almost every trace metal present in the sludge is found dissolved in the sludge liquor. The insolubility of many of the metal hydroxides is the primary reason for this phenomena.

Solubilities of compounds of the major ions in solution, e.g., sodium, chloride, and sulfate, do not vary appreciably with pH, and the concentrations of these ions in solution tend to rise to a point where the rate at which they are collected or formed is in balance with the rate at which they are rejected from the system in the sludge liquor. In direct lime and direct limestone slurry systems, sodium concentrations generally do not exceed a few thousand ppm. In sodium-based dual alkali systems, sodium concentrations in sludge liquors can range from 4,000 to 8,000 ppm or, if the filter cake is not washed well, even higher. For example, during sampling of the Utah and Parma dual alkali systems for the WES and Aerospace programs, the filter cake was not washed well and sodium levels (primarily Na_2SO_4 and NaCl) exceeded 20,000 ppm. In contrast, during periods of proper cake wash, cake samples from the Scholz dual alkali system showed less than 8,000 ppm of sodium.

Soluble chloride concentration is primarily a function of the chlorine/sulfur ratio in the coal being burned and the system water rejection rate. While chloride concentrations in liquors are generally less than 4,000 or 5,000 ppm, levels as high as 43,000 ppm have been reported for systems burning low sulfur western coal when a very tight liquor loop is maintained and when cooling tower blowdown is used for makeup water.

Sulfate concentrations are limited by the solubility product of gypsum. In direct lime or limestone slurry systems they generally do not rise above 5,000 to 8,000 ppm. However, soluble alkali or alkaline earth compounds containing magnesium or sodium are sometimes intentionally introduced into direct limestone systems to improve their performance. Under those circumstances sulfate concentrations can rise to 10,000 ppm or more. In well operated dual alkali systems (in which filter cake is well washed) soluble sulfate in the filter cake interstitial liquid generally ranges from 5,000 to 10,000 ppm.

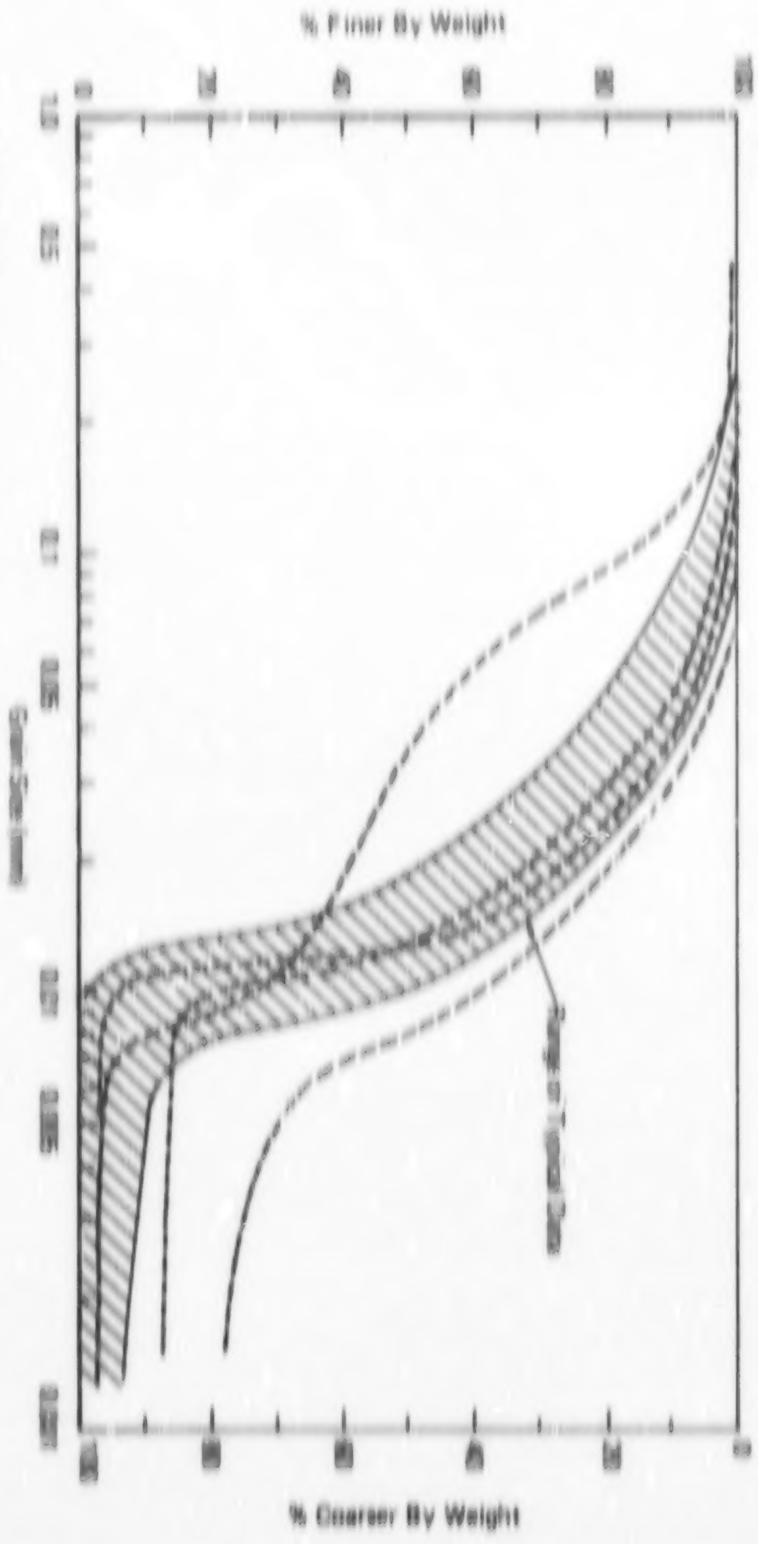
B. PHYSICAL AND ENGINEERING PROPERTIES OF UNTREATED FGD SLUDGES

The various physical properties of FGD sludges are important factors in the feasibility of almost every step of a candidate FGD sludge disposal scheme. Viscosity determines the feasibility and cost of transporting sludge slurries through pipelines. The ease and degree to which sludges can be dewatered affects costs of transportation, chemical treatment (if applied) and placement. The permeabilities of sludges affect the rate at which pollutants are leached. These, and the other physical and engineering properties of importance, all depend primarily on the percent solids in the sludge and on the morphology and size of the solid particles. Like the chemical composition of sludges, the morphology and size of sludge particles depends on, and can vary widely as a function of, the sulfur content of the coal, the way the boiler is operated, the type of particulate control employed, and the type of FGD system employed and the mode in which it is operated.

The results of measurements of physical and engineering properties that are presented in this section are representative of those available when this report was prepared. Programs involving the characterization of physical and engineering properties are still underway and additional work is anticipated. The physical and engineering properties that have been measured in the past have generally been those which have proven useful in predicting the behavior of soils in construction and landfill operations. As soil mechanics experts continue to examine FGD sludge in greater detail and apply new and different tests, a more complete understanding of the nature of FGD sludge will be possible. At present, Atterberg Limit Tests (both plastic and liquid) and consolidation tests are just beginning to be run on a limited number of sludge samples by the Civil Engineering Department of the University of Louisville. Also, as yet, no comprehensive triaxial compression tests have been run on FGD sludges. Data from these types of tests will be invaluable in predicting the behavior of FGD sludges in different disposal environments (9).

1. Particle Size Distribution

The solid phase of FGD sludges is comprised of particles normally ranging in effective diameter from about 1 to 200 microns. The family of particle size distribution curves shown in Figure IV-1 shows the general



Source: Reference 10

FIGURE IV-1   PARTICLE SIZE DISTRIBUTION OF FGD SLUDGES

distribution of sludge particle sizes as determined by sedimentation tests. The bimodal particle size distribution curve which is displaced to the left from the other curves was determined for a sample of sludge produced by an eastern direct limestone slurry process. About 40% by weight of the particles in that slurry had equivalent diameters greater than 50 microns; a second major portion of the solids had particle sizes within a relatively narrow band centered about ten microns. A bimodal distribution of that sort would be found if the sludge consisted of a mixture of large calcium sulfate/calcium sulfite crystals and smaller particles of fly ash or unreacted limestone.

Two distribution curves obtained on samples of eastern and western dual alkali sludges show about 10 to 20 weight % of the solids particles with equivalent diameters of less than a few microns. However, dual alkali systems do not necessarily produce sludges containing significant amounts of very fine particles. Other dual alkali systems under different process operating conditions have produced sludges in which bulk of the particle diameters ranged from 20 to 50 microns and larger (11).

2. FGD Sludge Densities and Dewatering Characteristics

Sludges produced by FGD systems are composed of two phases--sludge solids and entrained liquor (as well as entrained air). Depending on the proportions of each phase, the specific gravity of the product sludge can range from about 1.3 to 1.8. The true densities of the solid particles themselves, as shown in Table IV-4, are considerably higher, about 2.45 (1).

Since most unthickened slurries found in FGD processes contain on the order of 10% by weight suspended solids, they are frequently dewatered by one means or another prior to being discharged from the process to avoid the unnecessary discharge of large amounts of process liquor. The wet bulk densities of eight sludges after being dewatered in laboratory tests designed to simulate settling, settling followed by draining, filtration, and centrifugation are included in Table IV-4. Active dewatering by filtration or centrifugation generally produced a more dense sludge containing a higher percent of solids--wet bulk densities ranged from about 1.4 to 1.9 gram per cubic centimeter, and weight percent solids ranged from about 43 to 80%. The highest wet bulk densities and percents solids were observed for a

TABLE IV-4

TRUE AND BULK DENSITIES OF FGD SLUDGE SOLIDS

Plant	Location	Process	Date Sampled	Fly Ash (%)	True Density (g/cc)	Settled Density	Settled % Solids	Drained Density	Drained % Solids	Filtered Density	Filtered % Solids	Centrifugation Density	Centrifugation % Solids
Shawnee	Eastern	Limestone	3/1/73	20	2.48	1.45	45.0	1.51	57.7	1.65	65.0	1.56	55.0
			4/15/74	40	2.45	1.52	52.9	1.53	73.1	1.70	65.9	1.56	63.3
Shawnee	Eastern	Lime	3/29/74	42	2.53	1.36	43.4	1.37	45.3	1.55	56.0	1.37	48.9
Duquesne	Eastern	Lime	4/27/74	60	2.38	1.40	42.6	1.47	54.2	1.52	47.0	1.47	57.2
Cholla	Western	Limestone	9/1/74	59	2.53	1.39	46.7	1.44	58.9	1.48	53.4	1.60	60.9
Mohave	Western	Limestone	3/30/73	3	2.53	1.65	66.6	1.67	67.2	1.75	80.3	1.66	75.0
Parma	Eastern	Dual Alkali	7/28/74	7	2.43	1.25	40.0	1.39	43.9	1.57	57.0	1.48	58.9
Utah	Western	Dual Alkali	8/9/74	4	2.60	1.29	37.4	1.38	37.8	1.38	43.1	1.54	62.2

Source: Reference (3).

western limestone sludge containing very little fly ash. That particular sludge consisted almost entirely of gypsum which dewaters very well because it exists as rather large regular crystals.

The dewaterability of FGD sludges with actual process equipment tends to parallel the laboratory studies. Sludges containing primarily calcium sulfate can be dewatered to a greater extent than high calcium sulfite sludges. However, in practice, sludges are often not dewatered to the degree that can be achieved in the laboratory. Typical levels of percent solids which have been achieved are:

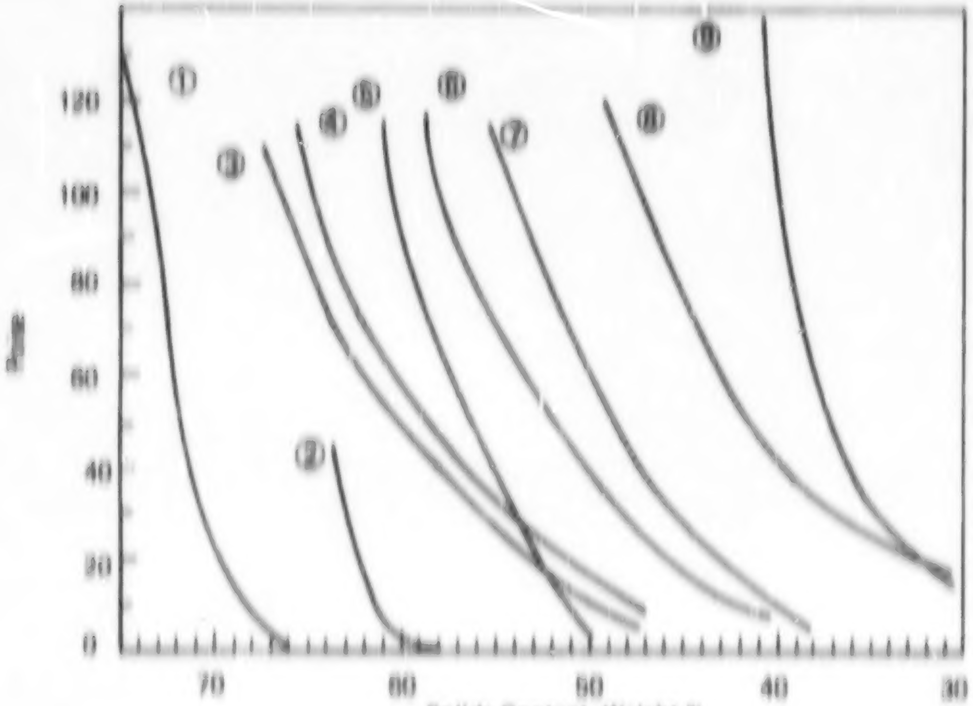
Sludge Type	Weight Percent Solids Thickening/Clarification	Filtration
Sulfite-rich $CaSO_3 \cdot 1/2\ H_2O$	20-35	35-75
Sulfate-rich $CaSO_4 \cdot 2H_2O$ (gypsum)	40-60	60-80

It is important to note that dewatering properties are strongly dependent upon the type and size of crystals grown. Since large gypsum crystals can be grown by controlling reaction rate, it is generally believed that gypsum solids can be more readily dewatered. However, the dewatering properties of sulfite-rich sludges can also be greatly improved by controlling crystal size and/or causing agglomeration of small crystals. In general, dual alkali systems have the capability for producing filter cakes containing up to 65% solids and higher because the calcium sulfite formation reaction is conducted in a crystallizer/reactor independent from the scrubber system. However, recent tests with direct lime and limestone systems have shown that sulfite crystal growth can also be controlled (resulting in improved dewatering properties) by closer control of system/boiler operating conditions.

3. Slurry Viscosities

Since slurry pumping is one potential means of FGD sludge transport, the viscosities of a number of FGD slurries were measured by Aerospace (1). Viscosities as a function of percent solids in the slurry are shown in Figure IV-2 for sludges from two western limestone (WLS) processes, an eastern limestone (ELS) process, two eastern lime (EL) processes, a western dual alkali (WDA) process, and an eastern dual alkali (EDA) process.

Curve	System	Source	Date	Fly Ash, %
①	WLS	Arizona Cholla Slurry Tank	4/1/74	58.7
②	WLS	SCE Mohave	3/30/73	3.0
③	ELS	TVA Shawnee	7/11/73	40.9
④	ELS	TVA Shawnee	6/15/74	40.1
⑤	ELS	TVA Shawnee	9/1/73	20.0
⑥	EL	Duquesne Phillips	6/17/74	59.7
⑦	EL	TVA Shawnee	3/19/74	40.5
⑧	WDA	Utah Gadsby Double Alkali	8/9/74	7.9
⑨	EDA	GM Parma Filter Cake	7/18/74	7.4



Source: Reference 1.

FIGURE IV-2 VISCOSITY OF DESULFURIZATION SLUDGE

A complete explanation of all of the factors underlying the wide range of viscosities observed is not available at the present time, but both the amount of fly ash and the morphology of the calcium/sulfur salt particles seem to play roles.

The two western limestone sludges contain very different amounts of fly ash. The one containing the greater amount was observed to be less viscous. However, both exhibit steep viscosity versus % solids curves characteristic of gypsum and materials of larger and more uniform grains. The three eastern limestone sludge curves represent the behavior of three samples taken from the same process at different times. The two samples containing about 40% fly ash were less viscous than the one containing 20%. The samples from the eastern lime processes seemed to depend in the same fashion on fly ash content although they were shifted to higher viscosities from the eastern limestone sludges. The two dual alkali sludges exhibited the highest viscosities of all of the samples tested. Particles in the dual alkali and eastern lime sludges that were not fly ash appeared to be somewhat fluffy agglomerates of very fine crystals as compared to the considerably larger rectangular plates found in the direct limestone sludges. The higher viscosities of the dual alkali and direct lime sludges as a group were attributed to that morphology difference (1).

In addition to illustrating the wide variation in slurry viscosity that one will encounter upon going from one process to another, the curves in Figure IV-2 also illustrate the very important point that day-to-day changes in boiler/FGD system operation are likely to cause significant changes in sludge viscosity. A decrease in the amount of fly ash collected or a change in morphology of the solids as a result of a change in operating conditions could change the energy required to pump the slurry.

4. Permeabilities of FGD Sludges

Shown in Table IV-5 are coefficients of permeability, k, determined for a number of FGD sludges in two studies. Included in Table IV-5 are determinations of void ratio, e, the quotient obtained by dividing the portion of the total sludge volume occupied by liquor and air by the volume occupied by solid phase. Coefficients of permeability were

TABLE IV-5

PERMEABILITIES OF UNTREATED FGD SLUDGES

Location	Process	Settled e^a	Settled k^b (cm/sec)	Compacted e^a	Compacted k^b (cm/sec)
Eastern	Limestone				
	Sample 1	1.53	1×10^{-4}	1.27	8×10^{-5}
	Sample 2	2.07	3×10^{-5}	1.56	1×10^{-5}
Eastern	Lime				
	Sample 1	1.83	2×10^{-4}	1.68	5×10^{-5}
	Sample 2	1.65	6×10^{-5}	1.42	1×10^{-5}
	Sample 3	7.25	1×10^{-4}	0.97	7×10^{-5}
Western	Limestone				
	Sample 1	0.96	3×10^{-5}	0.63	1×10^{-6}
	Sample 2	1.20	2×10^{-5}	1.20	1×10^{-5}
	Sample 3	0.75	8×10^{-4}	0.50	9×10^{-5}
Eastern	Dual Alkali				
	Sample 1	5.11	8×10^{-5}	4.17	3×10^{-5}
	Sample 2	2.19	2×10^{-4}	1.95	8×10^{-5}
Western	Dual Alkali	2.77	1×10^{-3}	2.61	1×10^{-4}

[a] e = Void ratio

[b] k = Coefficient of permeability

Source: References (1) and (10).

determined for samples which had been allowed to "drain" and for those which were "compacted". Measurements of the coefficient of permeability after draining were made by pouring a volume of sludge into a permeameter, allowing the solids to settle to equilibrium, and then performing the permeability measurement. Compacted samples were made either by vibrating the permeameter containing settled solids (10) or by using a plunger to further compact the settled solids (1).

With the exception of a western limestone and a western dual alkali sludge, which when drained were very permeable, all coefficients of permeability for drained samples ranged from about 2 x 10^{-3} to 2 x 10^{-4} cm/second. All samples showed a reduction in permeability after being compacted with permeabilities ranging from about 1 x 10^{-5} to 1 x 10^{-4} cm/second.

5. Compactability of FGD Sludges

Although FGD sludges are often characterized as being "gooey" or, at best, thixotropic (which is a misnomer), that behavior is due to the fact that many sludges are often only dewatered to solids contents ranging from less than 40 to perhaps 60%. If they are dewatered further by very efficient filtration or centrifugation, or by other means such as the simple addition of dry fly ash, they can be compacted in a manner not unlike that in which soil is compacted during the course of building roads or dams to produce a material which is quite firm and which will support considerable weight. For soils and soil-like materials there exists an optimum moisture content at which the material can be compacted to the greatest extent as evidenced by a maximum dry bulk density, for a given compactive effort.

At least two studies have been carried out in which the compactability of untreated FGD sludges was studied. Klym and Dodd (17) compacted a sludge composed of about equal amounts of calcium sulfite and calcium sulfate according to the standard Proctor method described in ASTM D698-70. A maximum dry bulk density of 84 lbs/cubic foot could be achieved if the sludge was dried to contain 77 weight % solids. However, even at 72% solids the sludge could be compacted, but a dry bulk density of only about 79 lbs/cubic foot could be achieved. In another study (11), a calcium sulfite sludge produced by a dual alkali process was compacted by the same standard Proctor method which was used for the direct limestone sludge. The dual alkali sludge could be compacted to a maximum dry density of about 72 lbs/cubic foot at 75% solids.

When confined in a mold, sludge samples have exhibited significant resistance to the action of compaction hammers. This resistance disappears when samples are removed from the mold. A few measurements of the unconfined compressive strengths of untreated dual alkali FGD sludges have been made, and as expected, unconfined compressive strengths were quite low, ranging from nil to 20 lbs/square inch (11). In essence, sludges exhibit only slight "apparent" cohesion, produced by capillary action (surface tension); this behavior is characteristic of fine granular soils. Such materials are very susceptible to disturbance such as vibration. Tests on sludge samples have shown that untreated sludges can "liquefy" under vibration (personal communication, J. Hagerty).

C. EFFECTS OF TREATMENT ON THE PHYSICAL AND ENGINEERING PROPERTIES OF FGD SLUDGES

Since the sludges produced by many FGD systems are, in fact, slurries or liquefiable sludges, they are usually disposed of in sludge ponds. Even after being allowed to settle in the pond for extended periods of time, the settled material is often still incapable of supporting sufficient weight to permit reclamation of the pond for productive use. To make sludge disposal areas more amenable to future productive use and to improve handling properties of sludges during disposal operations, a variety of treatment procedures for altering the physical properties of sludges have been proposed.

Most of the processes currently in use are often by private companies who consider the details of treatment to be proprietary. One general class of process which was studied by Ontario Hydro and reported in detail (12) involves the addition of lime or portland cement along with fly ash to the FGD sludge. Lime and fly ash undergo the well known pozzolanic reaction in which calcium from the lime reacts with silica in the fly ash to produce a cementitious calcium silicate matrix which tends to increase the structural strength and reduce the permeability of the sludge. Portland cement, which contains both calcium and silica, becomes cementitious itself when wetted and allowed to cure, and presumably the additional silica in any fly ash which is added can also participate in the cementing reaction.

One company, IU Conversion Systems (IUCS) is generally known to offer a treatment procedure based on lime/fly ash addition to process a reasonably hard material with low permeability. Other commercial vendors offer proprietary treatments which also produce relatively hard materials; e.g., Dravo Corporation which offers chemical treatment through use of an additive called Calcilox®. Another vendor, Chemfix, a division of the Carborundum Company, offers a procedure which can produce a treated material which has soil-like qualities instead of being a hard, concrete-like material.

Studies of the effects of a number of commercially available treatment procedures on the physical and engineering properties of FGD sludges have been conducted at WES. The treated materials were poured without compaction into cylindrical molds for curing. With the exception of a soil-like treated material which was remolded and compacted according to the standard Proctor method prior to measurement of permeability and unconfined compressive strengths, the other treated materials were simply removed from the cylindrical molds in which they were cured and then tested.

1. Effect of Treatment on Sludge Density

Shown in Table IV-6 are the bulk densities of the untreated and treated sludges studied in the WES program (10). Since at least some of the vendors wished to remain anonymous, the processors and the materials treated by them are identified only by letter codes. Bulk densities of treated materials were generally observed to range from about 90-110 lbs/cubic foot. In most cases Processes A, B, and E produced treated materials which were considerably more dense than the untreated sludge. In several cases, one process, D, produced a material that was less dense than the untreated sludge.

2. Effect of Treatment Process on Permeability

Shown in Table IV-7 are the measured coefficients of permeability for sludges treated by each of the five commercial processors (10). Process A generally reduced the coefficient of permeability by about two orders of magnitude. Treatment by Process B, which produced a soil-like material, resulted in permeabilities that were within an order of magnitude of those

TABLE IV-6

EFFECT OF SLUDGE TREATMENT ON BULK DENSITY

Location	Process	Bulk Density (lb/ft^3)					
		Untreated	Process "A"	Process "B"	Process "E"	Process "F"	Process "G"
Eastern	Lime	52	100	77	101	—	—
Eastern	Limestone	63	106	89	93	—	63
Eastern	Dual Alkali	52	96	91	96	—	53
Western	Limestone	80	109	80	111	81	57
Western	Dual Alkali	47	97	82	83	—	68

Source: Reference (10).

TABLE IV-7

EFFECT OF SLUDGE TREATMENT ON PERMEABILITY

Location	Process	Compacted Untreated	Process "A"	Process "B"	Process "E"	Process "F"	Process "G"
		Coefficient of Permeability (cm/sec)					
Eastern	Lime	1×10^{-5}	2×10^{-6}	2×10^{-6}	8×10^{-6}	—	—
Eastern	Limestone	8×10^{-5}	—	1×10^{-5}	3×10^{-6}	—	5×10^{-5}
Eastern	Dual Alkali	3×10^{-5}	1×10^{-7}	5×10^{-5}	5×10^{-11}	—	1×10^{-6}
Western	Limestone	1×10^{-5}	4×10^{-7}	4×10^{-5}	4×10^{-8}	5×10^{-6}	1×10^{-6}
Western	Dual Alkali	7×10^{-5}	9×10^{-7}	7×10^{-5}	7×10^{-7}	—	4×10^{-5}

Source: Reference (10).

of untreated sludges. Process E produced a wide range of changes in permeability. The permeability of an eastern lime sludge was increased by treatment while that of the others was decreased, in one case by more than six orders of magnitude.

3. Unconfined Compressive Strengths of Treated Sludges

Relatively little information is presently available on the strength of materials treated by processes in which the treatment formulae are known. Ontario Hydro did report on the development of strength in sludges treated with fly ash and either lime or portland cement. Their treated materials were sufficiently dry after treatment that they could be compacted by the Proctor procedure prior to curing. Compressive strengths after 1, 2, and 4 weeks of curing for samples treated with fly ash and lime are shown in Figures IV-3 and IV-4. With only two exceptions, all samples showed compressive strengths of about 100 lbs/square inch; more fly ash resulted in a higher strength. However, upon adding 15% portland cement, final strengths in the range of 600 to 800 lbs/square inch were achieved.

The results of unconfined compressive strength tests performed at WES on a number of treated sludges are shown in Table IV-8 (10). Processes A, F, and G all produced materials with compressive strengths in the range of 100-400 lbs/square inch. Process E materials had strengths of nearly 5,000 lbs/square inch.

The unconfined compressive strengths of the soil-like materials produced by Process B were measured after remolding test cylinders by Proctor compaction at the optimum moisture content. The observed strengths, ranging from about 20 to 50 lbs/square inch, were slightly greater than those discussed previously for untreated materials.

D. EFFECTS OF TREATMENT ON POLLUTANT MIGRATION FROM FGD SLUDGES

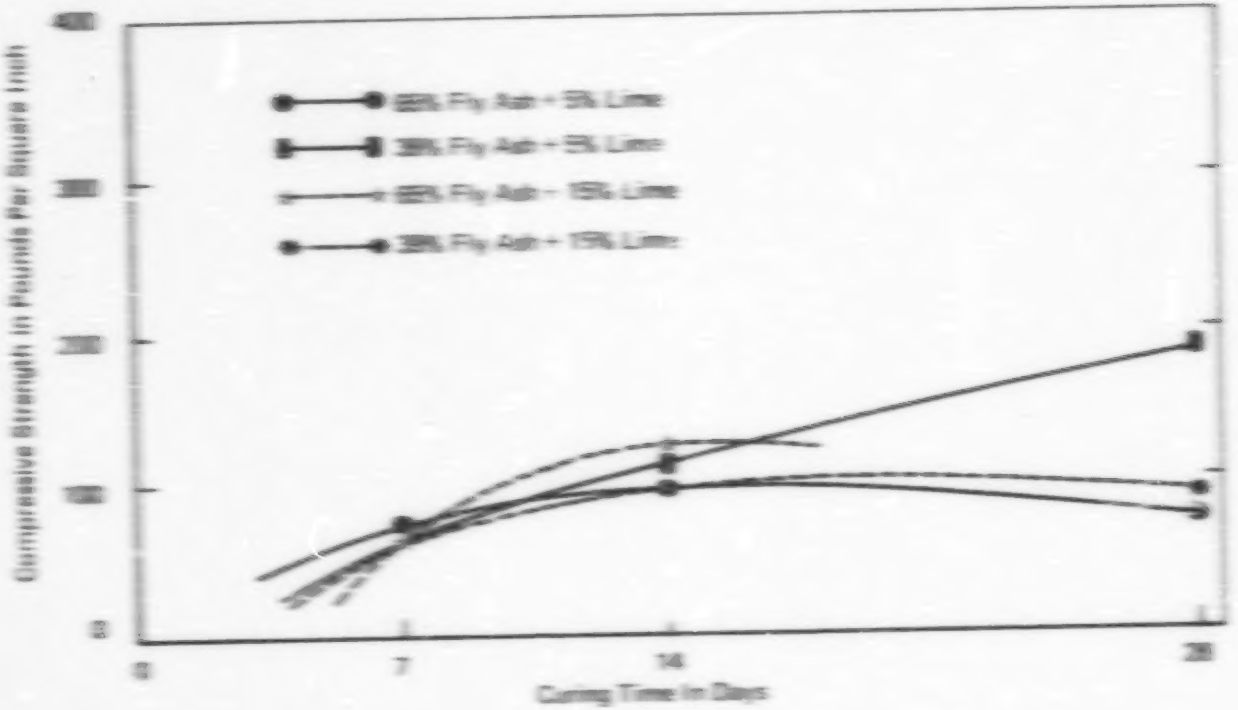
The impact of the pollutants contained in a mass of FGD sludge on the environment into which it is disposed does not depend solely on the amounts of pollutants in the liquid and solid phases of the sludge, but it also depends upon the rate at which interstitial liquor containing dissolved pollutants is flushed from the sludge and the rate at which pollutants in the solid phase of the sludge dissolve into the water permeating through

TABLE IV-8

UNCONFINED COMPRESSIVE STRENGTHS OF TREATED FGD SLUDGES

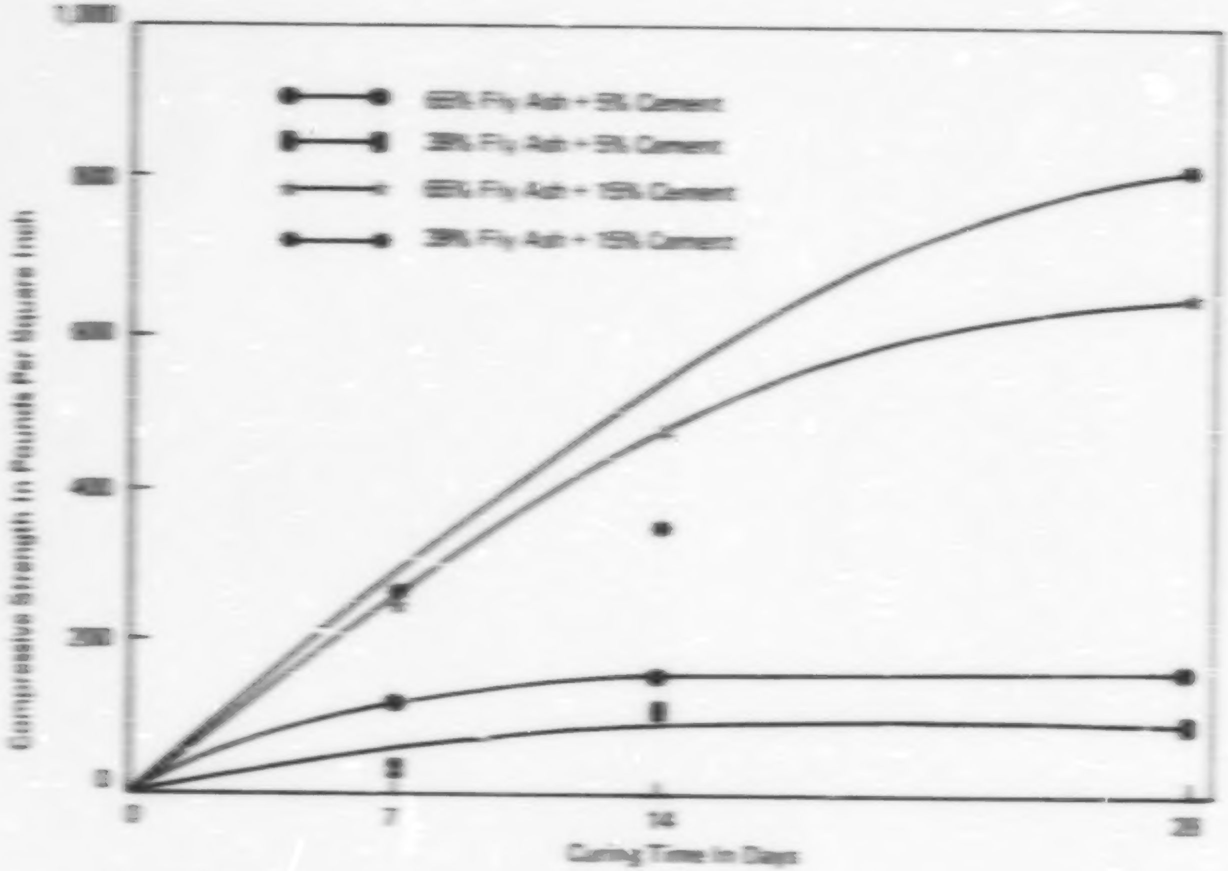
Location	Process	Unconfined Compressive Strength (psi)				
		Process "A"	Process "B"	Process "E"	Process "F"	Process "G"
Eastern	Lime	330	24	2,570	—	—
Eastern	Limestone	—	45	720	—	243
Eastern	Dual Alkali	188	43	2,220	—	86
Western	Limestone	403	35	4,486	396	126
Western	Dual Alkali	337	23	1,374	—	144

Source: Reference (30).



Source: Reference 12.

FIGURE IV-3 RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND CURING TIME FOR SLUDGE TREATED WITH FLY ASH AND QUICKLIME (ONTARIO HYDRO)



Source: Reference 12.

FIGURE IV-4 RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND CURING TIME FOR SLUDGE TREATED WITH FLY ASH AND CEMENT (ONTARIO HYDRO)

it. In addition to enhancing the disposability of sludges by improving their dimensional stability, sludge treatment processes can reduce pollutant migration by decreasing the permeability of the sludge mass, decreasing the solubility of potential pollutants, or both.

Little information is presently available concerning the leaching of potential pollutants from treated and untreated sludges, although a considerable amount of work on leaching properties is now underway. Concentrations of a number of pollutants in leachate samples taken at the beginning and end of accelerated leaching tests which were performed on four different sludges are shown in Table IV-9. Concentrations of sulfate and chloride as well as total dissolved solids (TDS), the concentration in the leachate after 50 pore volumes of leach liquor, had passed through the sludge and reached similar levels even though the initial concentrations in the sludge liquors were significantly different. In all cases TDS had fallen to about 1,900-2,500 ppm and sulfate had fallen to about 1200 ppm; these levels probably reflect the equilibrium solubility of the calcium sulfate component of the sludge solids. The other chemical species showed the same tendency to level off to similar concentrations after 50 pore volumes of leaching had taken place.

One attempt to evaluate the effect of sludge treatment on pollutant leaching conducted by Aerospace (1) involved a comparison of the accelerated leaching behavior of samples of untreated sludges with the behavior of the same materials after treatment. The effect of treatment on the concentration of a number of pollutants in the first pore volume and 50th pore volume of leachate collected from treated and untreated eastern limestone sludge is shown in Table IV-10. In most cases, the concentrations of substances in the first pore volume were somewhat lower for the treated material. Concentrations of major soluble species such as chloride and sulfate as well as TDS were reduced by about a factor of 2 to 3. Concentrations of arsenic, chromium and selenium were also substantially lower. Cadmium levels in the first pore volume of leachate were essentially the same, but levels of copper, lead and zinc in the first pore volume were slightly higher for the treated material than for the untreated material.

Initial results obtained from the Shawnee Field Test Program (13) indicate that treatment can produce similar reductions in the concentrations

TABLE IV-9

COMPARISON OF THE CHEMICAL CONSTITUENTS IN SLUDGE LIQUORS WITH LEACHATE AFTER 50 PORE VOLUME DISPLACEMENTS

(Concentrations in mg/liter)

	Eastern Limestone Shawnee (Clarifier Underflow)		Western Limestone Cholla (FDS Tank Discharge)		Eastern Dual Alkali Parma (Unwashed Filter Cake)		Western Limestone Mohave (Centrifuge Cake)	
	Liquor[a]	Leachate	Liquor[a]	Leachate	Liquor[a]	Leachate	Liquor[a]	Leachate
As	0.14	0.01	<0.004	<0.0004	<0.004	<0.002	0.012	<0.004
Be	0.054	0.004	0.14	0.004	<0.005	0.004	0.02	0.004
Cd	0.005	<0.001	0.011	0.001	<0.02	<0.001	0.05	<0.001
Cr	0.08	0.003	0.14	0.002	<0.02	<0.001	0.4	0.003
Cu	0.01	0.010	0.20	0.01	0.06	<0.001	0.6	0.010
Pb	0.25	0.01	0.01	0.001	0.55	<0.001	0.04	<0.001
Hg	<0.05	<0.00005	0.07	0.00005	0.0009	<0.00005	<0.05	<0.00005
Se	0.08	0.006	2.2	0.05	0.067	0.010	0.120	0.004
Zn	0.20	0.045	0.11	0.04	0.63	0.04	0.18	0.045
Cl	2,300	120	1,700	110	4,400	95	43,000	120
F	6.2	<0.2	0.7	6.1	60	0.2	30	<0.2
SO_3	60	25	0.9	9.0	160	30	1.5	0.3
SO_4	10,000	1,200	4,000	1,150	30,000	1,100	8,000	1,250
pH	8.3	5.0	3.04	5.9	12.76	6.1	6.7	4.45
TDS	15,000	2,400	8,700	1,900	72,000	1,650	95,000	2,100

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[a] Liquor analysis for liquor occluded with sludge solids as disposed.

Source: Reference (1).

TABLE IV-10

COMPARISON OF THE CHEMICAL CONSTITUENTS IN EASTERN LIMESTONE SLUDGE LEACHATE WITH CHEMFIX CHEMICALLY TREATED SLUDGE LEACHATE

	Sludge - Aerobic		Chemfix - Aerobic	
	1st Pore Vol.	50th Pore Vol.	1st Pore Vol.	50th Pore Vol.
As	0.14	0.01	0.04	0.006
Cd	0.003	<0.001	0.003	<0.001
Cr	0.09	0.003	0.04	<0.001
Cu	0.01	0.010	0.05	0.005
Pb	0.25	0.01	0.35	<0.001
Hg	<0.05	<0.00005	<0.005	<0.0005
Se	0.08	0.006	0.01	0.002
Zn	0.20	0.045	0.5	0.065
Cl	2300	120	1400	60
F	6.2	<0.2	0.9	0.2
SO_4	10,000	1200	3000	650
TDS	15,000	2400	7000	1500
pH	8.3	5.0	4.70	6.01

Source: Reference (1).

of major soluble species in actual test pond leachates. Whether or not the concentrations of trace substances are reduced has not yet been established with any degree of certainty.

In the WES program to evaluate the chemical treatment of sludges, five different FGD sludges were each treated by a number of commercial processors, and both the treated and untreated materials are being subjected to long-term leaching experiments to assess the effects of treatment on sludge pollution potential. A large number of substances, both trace and major constituents, are being measured in the leachate collected from the leaching columns. At the present time only preliminary data are available and results are inconclusive. In some cases there is evidence that treatment may not have reduced the concentration of dissolved solids in the leachate over the first few pore volume displacements, while in other cases there is a definite improvement in the leachate quality.

In summary, it is apparent, based upon the information available at the present time, that treatment processes, in general, improve the handling properties and in most cases increase the strength and reduce the permeability of FGD sludges. However, no definitive conclusions can be drawn as yet concerning the ability of treatment processes to reduce the *concentrations* of contaminants in leachate (leachate *quality*) from treated sludges.

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V. MINE DISPOSAL OF FGD SLUDGE

In this study, mines are evaluated for their feasibility as disposal alternatives for flue gas desulfurization (FGD) sludges. Metallic, nonmetallic, and coal mines are initially screened for their available capacity, location, and ease of sludge placement. Those which appear most technically promising are subsequently reviewed for environmental impacts, regulatory constraints, operation, and monitoring. Because of the overview nature of this report, mines are reviewed in terms of the conditions believed most typical for a given mineral, mining method, and region. However, mines of any method and region may actually be a promising local disposal alternative with regard to site-specific hydrogeologic and environmental factors.

A. REVIEW OF THE MINING INDUSTRY

In 1971 there were about 0.6 billion tons of surface and underground coal produced, 0.2 billion tons of underground metal and nonmetal minerals produced, and about 2.5 billion tons of open pit metal and nonmetal minerals produced. Of the many commodities mined, bituminous coal accounted for the largest percentage of lands used for mining. In 1971 there were about 73,200 acres used for bituminous coal mining operations, of which about 48,000 acres were active mining areas. The total of all metallic and nonmetallic mineral operations (excluding coal) used about 130,000 acres. Of these, sand, gravel, and stone accounted for the greatest amount of land use--together about 71,400 acres. Table V-1 summarizes the land utilization and reclamation by mining industry in the United States through 1971.

The greatest amount of land reclamation occurs in coal mining, and the least for metal mines. Because surface mining of coal usually allows full seam extraction, reclamation does not inhibit future resource recovery. Reclamation of most lands used for metallic and nonmetallic mineral mines would, however, often unfavorably affect future resource extraction.

1. Coal Mining

a. Coal Production

The coal fields of the continental United States are shown in Figure V-1 (there are reserves in Alaska not shown) broken down by region--Eastern,

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TABLE V-1

LAND UTILIZED AND RECLAIMED BY THE MINING INDUSTRY IN THE UNITED STATES IN 1930-71 and 1971, BY SELECTED COMMODITY

Commodity	Land utilized, acres[a]		Land reclaimed, acres[a]		Percent reclaimed,
	1930-71	1971	1930-71	1971	1930-71
Metals:					
Copper	166,000	19,100	4,810	1,410	2.9
Iron ore	108,000	8,620	4,630	2,330	4.3
Uranium	12,800	1,950	810	440	6.3
Other[b]	237,000	6,740	33,000	8,400	13.9
Total[c]	524,000	36,400	43,300	12,600	8.3
Nonmetals:					
Clays	167,000	7,460	58,700	4,330	35.1
Phosphate rock	77,300	10,200	12,300	2,070	15.9
Sand and gravel	660,000	46,400	197,000	34,300	29.8
Stone	516,000	23,000	124,000	9,480	24.0
Other[d]	138,000	8,030	14,100	3,070	10.2
Total[c]	1,560,000	95,100	406,000	53,200	26.0
Solid Fuels:					
Bituminous coal	1,470,000	73,200	1,000,000	94,600	68.0
Other[e]	105,000	1,710	14,100	2,230	13.4
Total[c]	1,570,000	74,900	1,010,000	96,900	64.3
Grand Total[c]	3,650,000	206,000	1,460,000	163,000	40.0

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[a] Includes area of surface mine excavation, area used for disposal of surface mine waste, surface area subsided or disturbed as a result of underground workings, surface area used for disposal of underground waste, and surface area used for disposal of mill or processing waste.

[b] Bauxite, beryllium, gold, lead, manganese, mercury, molybdenum, nickel, platinum-group metals, silver, titanium (ilmenite), tungsten, vanadium, and zinc.

[c] Data may not add to totals shown because of independent rounding.

[d] Aplite, asbestos, barite, boron minerals, diatomite, emery, feldspar, fluorspar, garnet, graphite, greens and marl, gypsum, kyanite, lithium minerals, magnesite, mica, millstones, olivine, perlite, potassium salts, pumice, pyrites, salt, sodium carbonate, talc, tripoli, vermiculite, and zeolite.

[e] Anthracite and peat.

Source: Land Utilization and Reclamation in the Mining Industry, 1930-1971, United States Department of the Interior, Bureau of Mines, 1974.

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PB

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1.0
1.1
2.0
1.8
1.25
1.4
1.6

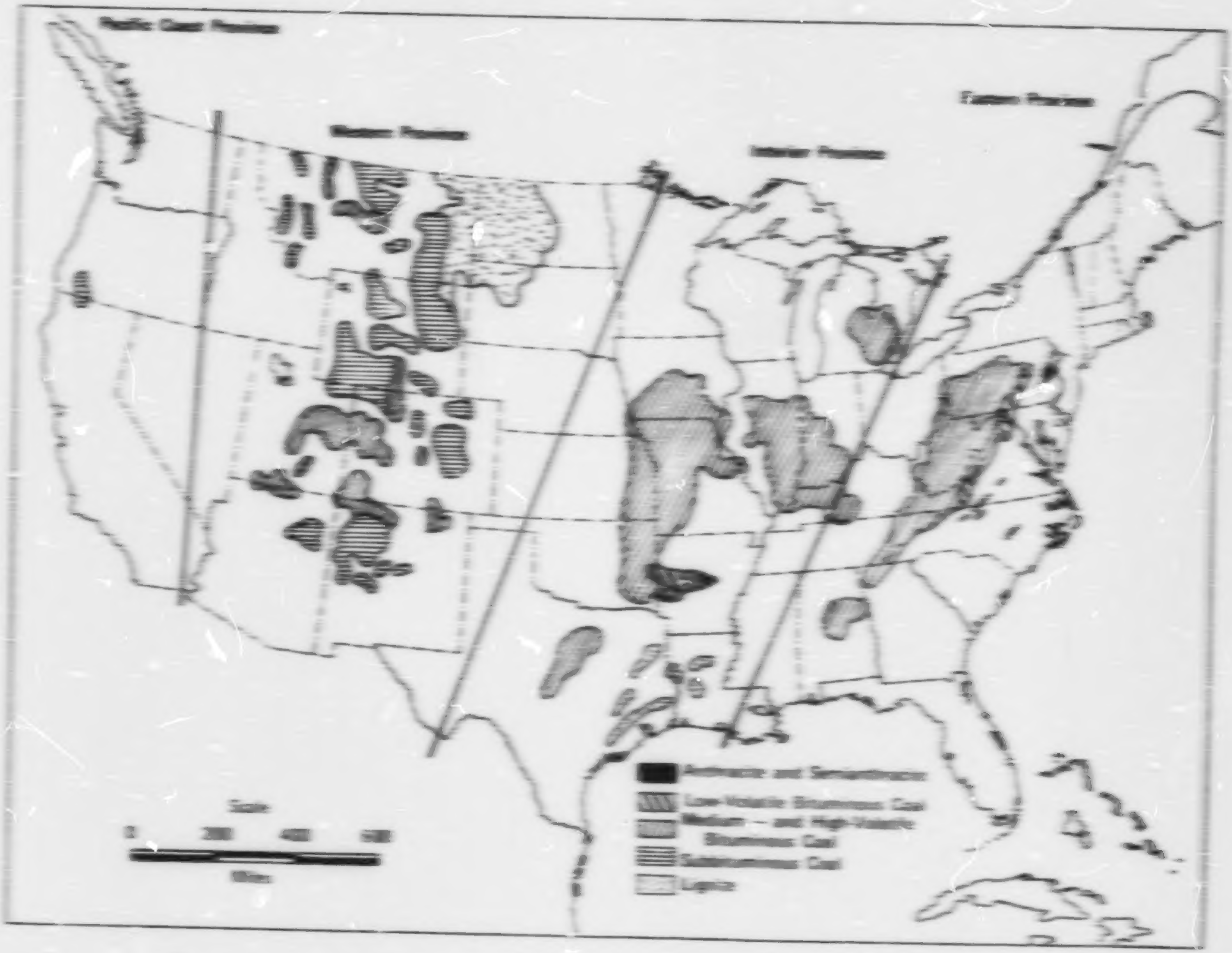

Pacific Coast Province
Western Province
Interior Province
Eastern Province
Anthracite and Semianthracite
Low-Volatile Bituminous Coal
Medium – and High-Volatile Bituminous Coal
Subbituminous Coal
Lignite
Scale
0
200
400
600
Miles

FIGURE V-1 COAL FIELDS OF THE UNITED STATES

Interior, Western, and Pacific Coast. There are large reserves of coal occurring principally in about 25 states, but the major production is currently from nine states (Alabama, Illinois, Indiana, Kentucky, Ohio, Pennsylvania, Virginia, West Virginia, and Wyoming). The future production is expected to shift as greater volumes are produced from Western states. As shown in Figure V-1, states in the Western regions are rich in low-sulfur coal, while coal reserves in the Eastern and Interior regions are predominantly medium- and high-sulfur coal.

About half of the coal currently produced in the United States is surface mined; the other half is produced from underground coal mines. Production by mining method is shown in Figure V-2. The majority of coal production in the Western region involves surface mining methods, while in the Eastern and Interior regions, underground mining accounts for roughly 60% of the total coal production (1973). Tables V-2 and V-3 show the number of mines and distribution of coal production by mining method and state.

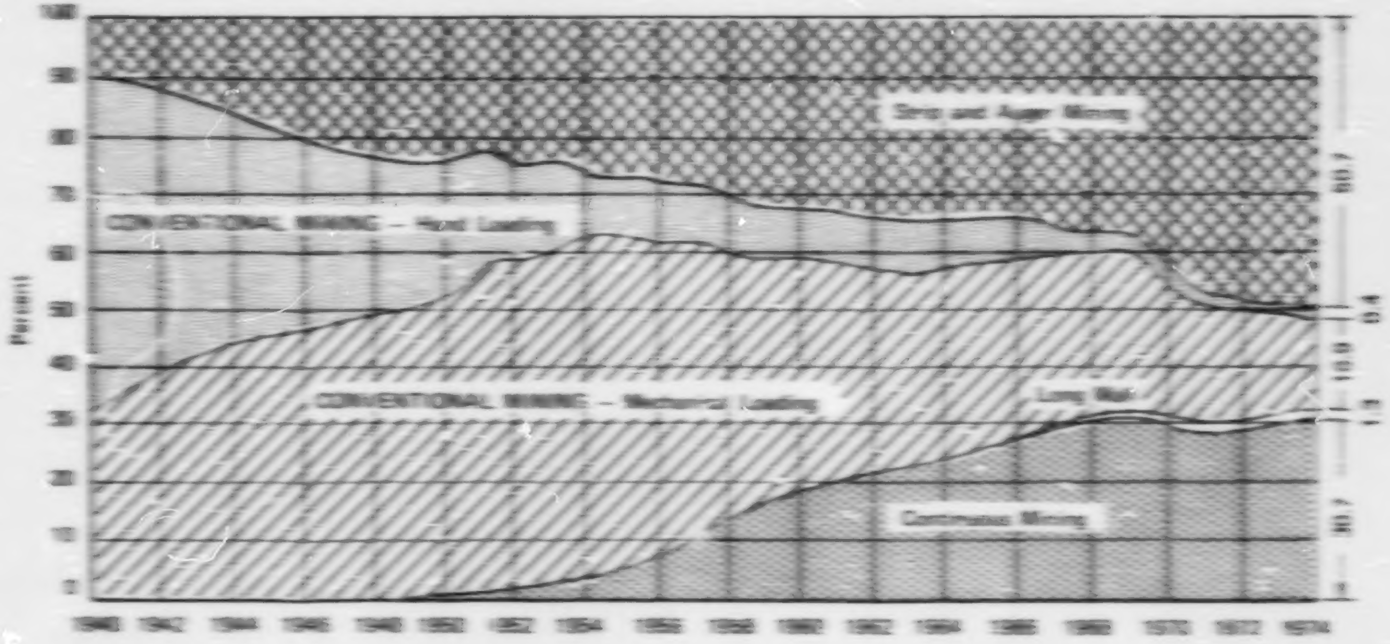
b. Coal Mining Methods

Strip Coal Mining

Mining practice in strip coal mines mostly involves the use of draglines and shovels for overburden removal, smaller shovels and front-end loaders for coal digging, and trucks for hauling. In a few cases, scrapers and bucket wheel excavators are used in soft overburdens. In strip coal mining where the overburden is relatively soft or can be loosened somewhat by gentle blasting, the dragline is the preferred machine to use for digging and casting. If the formations over the coal seam are hard and compact and tend to break into blocky or hard-to-handle aggregates of blocky chunks, then large shovels are preferred. Roughly half of the surface mining involves draglines, while the other half involves shovels.

The conventional strip mining method for relatively flat or level areas is known as "area stripping." A tipical area strip mining operation is shown in Figure V-3. Area stripping is common in the Western and Interior coal mining regions.

When coal is open-surface mined on steep slopes, the system is called "contour stripping." These steep slope conditions prevail in the Eastern



Source: U.S. Bureau of Mines.

FIGURE V-2 MINING METHODS USED IN U.S. BITUMINOUS COAL PRODUCTION

TABLE V-2

PRODUCTION OF BITUMINOUS COAL AND LIGNITE IN U.S. BY REGION UNDERGROUND, STRIP AND AUGER MINING (1973)

(thousands of short tons)

	Underground	Strip and Auger	Total
Eastern Province			
Alabama	7,892	11,901	19,793
Kentucky (Eastern)	41,500	32,500	74,000
Maryland	64	1,690	1,754
Ohio	16,205	29,140	45,345
Pennsylvania	46,255	30,391	76,646
Tennessee	4,785	4,208	8,993
Virginia	23,339	10,530	33,869
West Virginia	95,448	19,791	115,239
	235,488	140,151	375,639
Interior Province			
Arkansas	3	455	458
Illinois	32,578	28,971	61,549
Indiana	782	24,485	25,267
Iowa	385	470	855
Kansas	---	1,145	1,145
Kentucky (Western)	21,900	31,100	53,000
Missouri	---	4,980	4,980
Oklahoma	85	2,540	2,625
Texas (lignite)	---	6,945	6,945
	55,733	101,091	156,824
Western Province			
Arizona	---	2,965	2,965
Colorado	3,377	2,855	6,232
Montana:			
Bituminous	20	9,530	9,550
Lignite	---	400	400
New Mexico	1,062	8,278	9,340
North Dakota (lignite)	---	7,400	7,400
Utah	5,105	35	5,140
Wyoming	680	12,920	13,600
	10,244	44,383	54,627
Pacific Coast Province			
Alaska	---	700	700
Washington	35	3,175	3,210
	35	3,875	3,910
Total	301,500	289,500	591,000

TABLE V-1

NUMBER OF COAL MINES BY STATES

(1973)

	Strip[a]	Underground[b]
Eastern Province		
Alabama	29	0
Kentucky	76	51
Maryland	3	-
Ohio	75	15
Pennsylvania	62	44
Tennessee	16	3
Virginia	9	14
West Virginia	62	93
	332	248
Interior Province		
Arkansas	1	-
Illinois	21	20
Indiana	13	2
Iowa	2	1
Kansas	3	-
Missouri	7	-
Oklahoma	4	-
Texas (Lignite)	2	-
	53	23
Western Province		
Arizona	1	-
Colorado	4	3
Montana	4	-
New Mexico	2	1
North Dakota (Lignite)	8	-
Utah	-	5
Wyoming	9	1
	28	10
Pacific Coast Province		
Alaska	1	-
Washington	1	-
	2	
Total	451	281

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[a] Producing over 150,000 tons/year.
[b] Producing over 300,000 tons/year.

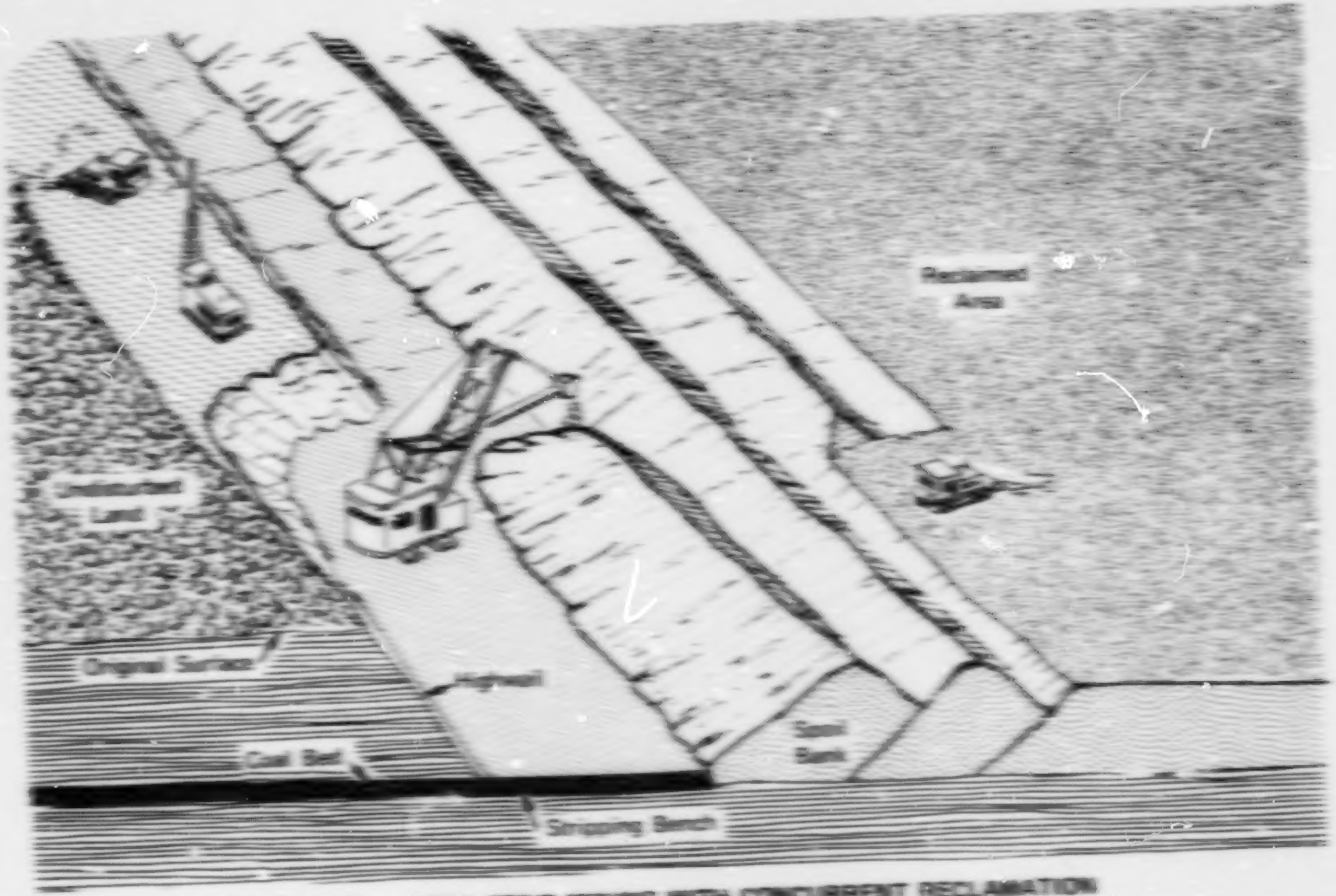

Reclaimed Area
Undisturbed Land
Original Surface
Highwall
Coal Bed
Stripping Bench
Spoil Banks

FIGURE V-3 AREA STRIP MINING WITH CONCURRENT RECLAMATION

coal region. In conventional contour stripping, spoil or waste is stripped and dumped downhill from the cut, as shown in Figure V-4. A variation of contour stripping is known as "haulback" or "block stripping" (Figure V-5), where spoil is removed horizontally into the mined-out cut rather than dumped downhill.

Underground Coal Mining

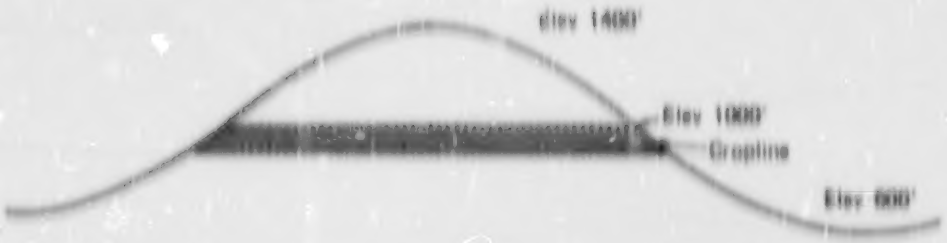
There are two basic underground coal mining methods: room and pillar, and longwall. Underground coal mines are often classified as slope, drift, or shaft mines, depending upon the method of access rather than the mining method used. Figure V-6 shows sketches of these three possibilities.

Room and pillar mines remove the coal in "rooms" and leave "pillars" to support the roof. If the pillars are not robbed, the coal extraction in this procedure is on the order of 50%. If geologic and roof conditions permit and if surface caving can be allowed, the pillars can be robbed (removed) as one retreats back to the access opening. This can increase extraction to 70-80%. Complete extraction through pillar robbing is not technically feasible, as roof collapse following robbing limits access to nearby pillars.

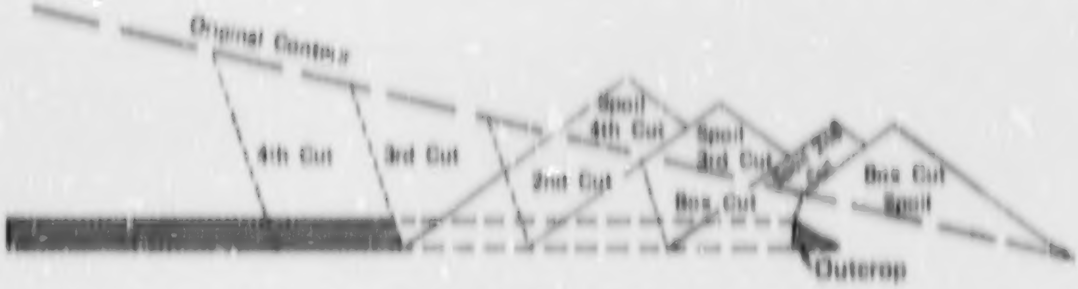
Room and pillar coal extraction can be "conventional" or "continuous." Conventional means that the coal is extracted in a series of steps which are: undercutting the coal, drilling, blasting, loading, and shuttle car haulage to main haulage belts or rails. Continuous methods use a continuous mining machine which cuts the coal, loads it, and delivers it to shuttle cars (which really makes the system only semi-continuous) or to conveyor belts for removal from the mine. In most room and pillar systems another important step is to place roof bolts for supports as the mining proceeds.

Longwall mining systems rely on the controlled caving of the roof. The system consists of a coal cutting machine, chain conveyor system, and hydraulic movable roof support. Most U.S. coal mines using longwall techniques also produce coal by room and pillar methods. Hence, coal production from any mine is rarely all from the longwall mining operation itself.

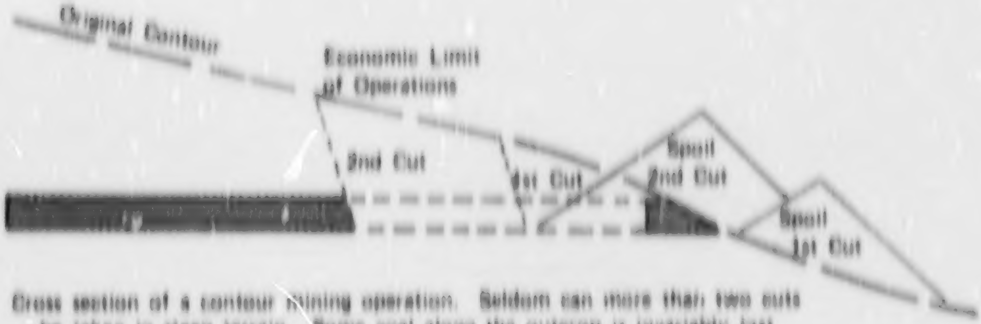
The operation of longwall coal systems is more nearly continuous (when they operate successfully) than room and pillar mining, with coal


Elev 1400'
Elev 1000'
Cropline
Elev 600'

Typical section showing coal seam outcrop in steep terrain suitable only for contour mining.


Original Contour
4th Cut
3rd Cut
2nd Cut
Spoil
4th Cut
Spoil
3rd Cut
Box Cut
Box Cut
Spoil
Outcrop

Cross section (end view) of conventional surface mining showing sequence of operation.

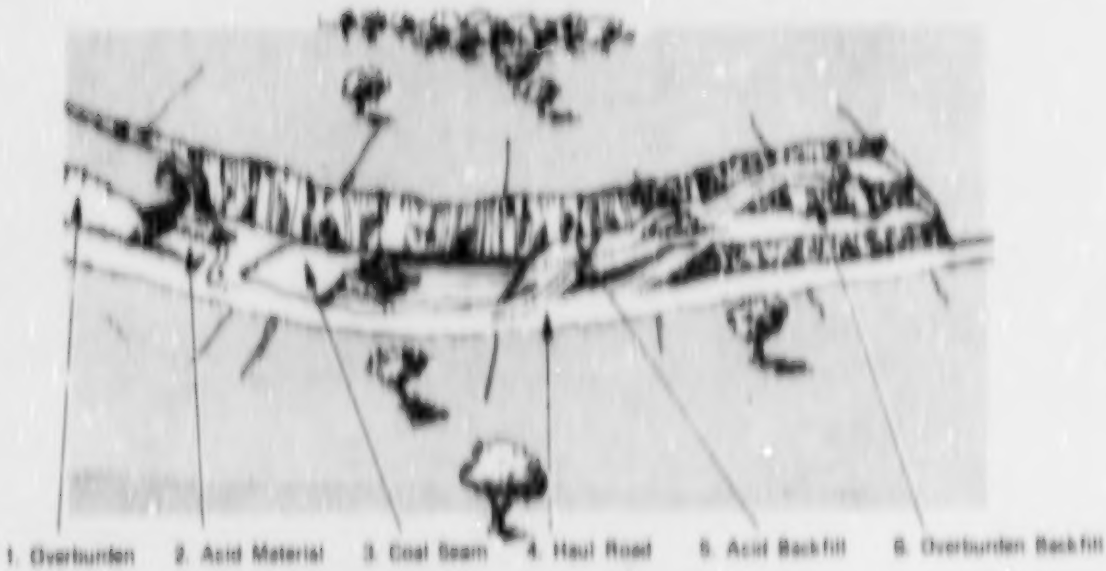

Original Contour
Economic Limit
of Operations
2nd Cut
1st Cut
Spoil
2nd Cut
Spoil
1st Cut

Cross section of a contour mining operation. Seldom can more than two cuts be taken in steep terrain. Some coal along the outcrop is invariably lost as it is soft, weathered, and oxidized, thereby losing its heat value. The width of the weathered portion is highly variable.

Source: Cassidy, S.M., *Elements of Practical Coal Mining*, Society of Mining Engineers, New York, 1973.

FIGURE V-4 CONTOUR COAL STRIPPING

The Truck Haulback Method


1. Overburden
2. Acid Material
3. Coal Seam
4. Haul Road
5. Acid Backfill
6. Overburden Backfill

The Scraper Haulback Method

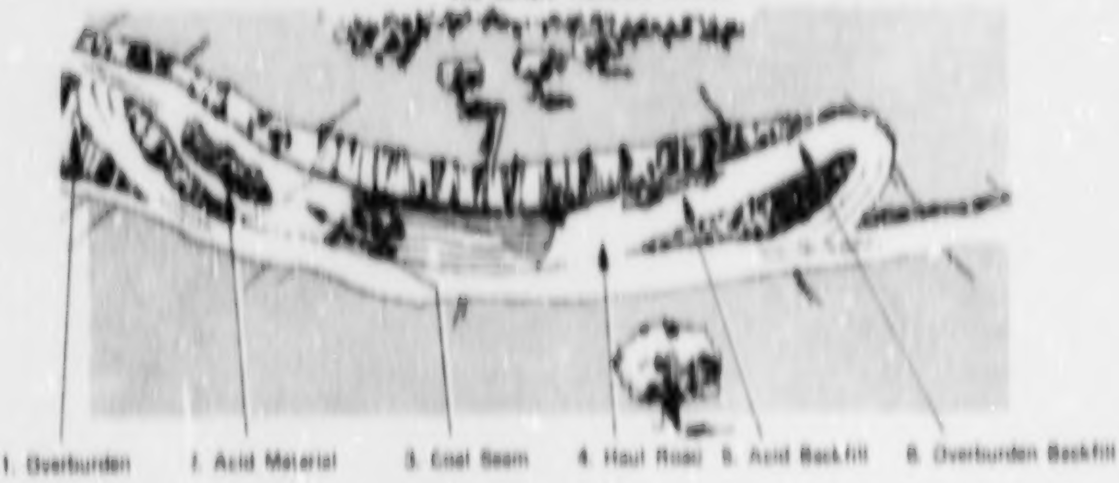
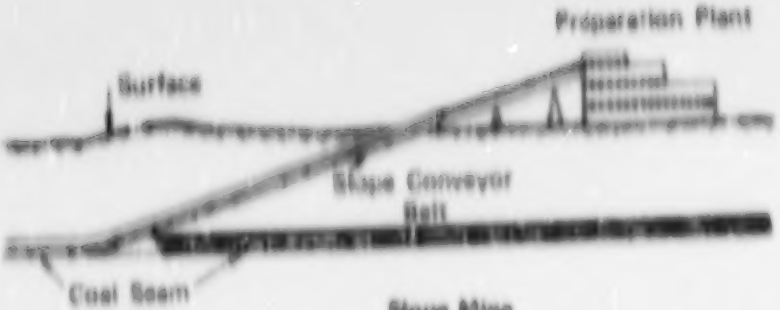
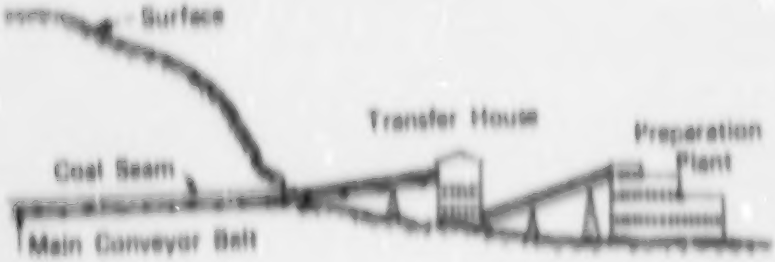

1. Overburden
2. Acid Material
3. Coal Seam
4. Haul Road
5. Acid Backfill
6. Overburden Backfill

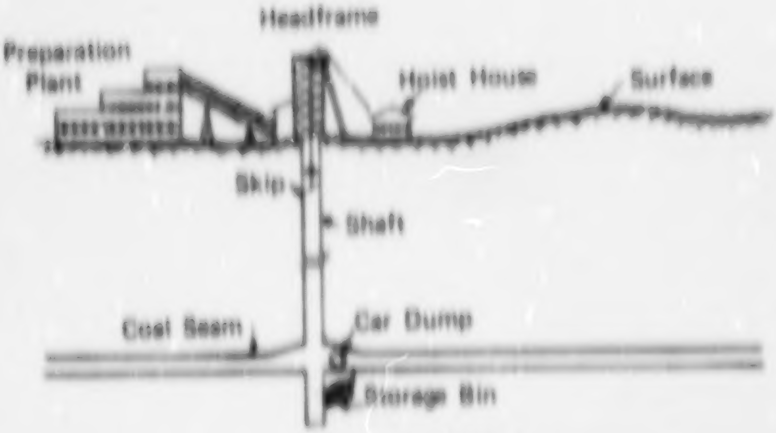
FIGURE V-5 BLOCK METHODS OF CONTOUR STRIP MINING


Preparation Plant
Surface
Slope Conveyor Belt
Coal Seam

Slope Mine


Surface
Transfer House
Preparation Plant
Coal Seam
Main Conveyor Belt

Drift Mine


Headframe
Preparation Plant
Hoist House
Surface
Skip
Shaft
Coal Seam
Car Dump
Storage Bin

Shaft Mine

Source: Cassidy, S.M., *Elements of Practice: Coal Mining*, Society of Mining Engineers, New York, 1973.

FIGURE V-6 TYPES OF UNDERGROUND COAL MINES

cutting, removal, and prop advance going on steadily. When the props are advanced, the unsupported roof caves and leaves what is known as gob area.

A recent development in longwall mining has been the adaptation of the method of what is known as "shortwall mining." Shortwall mining involves use of heavy-duty advancing props just as in conventional longwall mining; but instead of a coal cutting machine and conveyor removal system, a continuous mining machine is used.

Longwall mining methods (including shortwall mining) cannot be used in all underground coal mines in the United States. Application of longwall operations are limited to areas where the surface above can be disturbed and where the coal to be mined occurs in configurations amenable to the longwall layout. It is generally not applicable in areas where there is massive or difficult-to-cave roof. Also, in some circumstances, the high dust levels created may be difficult to control to the low limits specified by Federal Government safety regulations. As a result, longwall mining currently accounts for only about 3% of the total underground coal production. This amount is slowly, but steadily, increasing.

c. Capacity for Sludge Disposal in Coal Mines

The weight of dry sludge produced can vary from 5% (not including ash) of the weight of coal burned for low-sulfur coal to as much as 35% (including ash) for high-sulfur coal. Taking into account the water occluded with solids, these weights would increase by as much as 50% to 100%. Based upon current projection of FGD sludge production (see Table 1-1), FGD sludge with ash may require as much as 20,000 acre-feet of disposal space in 1980 (less than 10% of the volume of coal mined) and that by 1985 the annual volume could reach 60,000 acre-feet (about 20% of the volume of coal mined).

By comparing the amount of sludge from stack gas scrubbing with the amount of coal burned, it is apparent that the annual volume of FGD sludge produced is considerably less than the volume of coal mined (mined coal includes production for power plants as well as for industrial raw material requirements). However, the volume of coal mined is not necessarily the volume of the available void for sludge disposal. In surface mines, for example, sludge disposal would have to be scheduled to keep up with the continuous extraction-reclamation process to utilize the entire volume of the extracted seam. In addition, in surface mines, sludge could not be placed at the coal seam outcrop due to potential slope stability and sludge erosion problems. In underground mines, increased use of pillar robbing and longwall mining techniques allows roof collapse to significantly fill the void left from seam extraction and to render some remaining voids inaccessible. There is no data on the total amount of coal produced from a combination of longwall and pillar robbing practices. However, as the current national coal recovery estimate is about 60% from all underground mines, nearly one-half of the mine space must be devoted to operations allowing caving.

2. Metal and Nonmetal Mining

a. Metal and Nonmetal Mineral Production

Tables V-4 and V-5 show the number and distribution of mines by size and general mining method that are annually producing substantial quantities of metallic and nonmetallic minerals. By far, the greatest number of mines involve the production of sand, gravel, and stone (including limestone). Most of these mines are open pit or quarry. However, there is significant underground mining of limestone. Significant underground mining of copper, lead, zinc, iron, and salt also occurs.

b. Metal and Nonmetal Mining Methods

Underground Metal and Nonmetal Mining

In underground metal and nonmetal mining (excluding coal), access to the ore can be through vertical or sharply inclined shafts, or through horizontal or slightly dipping passageways. These passageways are called adits in metal mines.

Once underground, passages are driven to get to and develop the actual area where the ore is extracted. These passages are usually horizontal and are called drifts. Passages that cut across the drifts are crosscuts. To get to the ore body from the openings, one drives raises (upward) or winzes (downward). The drifts and crosscuts are used as haulage ways to get ore out of the mine. Haulage equipment can be tracked (rail), trackless (truck), conveyor belt, or in a few cases, hydraulic, where mined ore is pumped through pipelines.

TABLE V-4

NUMBER OF DOMESTIC METAL AND NONMETAL MINES IN 1973, BY COMMODITY AND MAGNITUDE OF CRUDE ORE PRODUCTION[a]

Commodity	Total Number of Mines	100,000 to 1,000,000 Tons	1,000,000 to 10,000,000 Tons	More Than 10,000,000 Tons
Metals				
Bauxite	15	5	-	-
Copper	65	15	17	11
Gold:				
Lode	29	2	2	-
Placer	50	2	-	-
Iron Ore	69	22	21	5
Lead	36	11	4	-
Mercury	21	-	-	-
Silver	41	3	-	-
Titanium: ilmenite	7	-	7	-
Tungsten	25	1	-	-
Uranium[b]	75	16	1	-
Zinc	28	20	-	-
Other[c]	12	2	5	1
Total Metals	473	98	59	16
Nonmetals				
Abrasives[d]	9	-	-	-
Asbestos	6	2	2	-
Barite	41	16	-	-
Boron minerals	3	-	1	-
Clays	1,420	157	-	-
Diatomite	13	7	-	-
Feldspar	21	8	-	-
Fluorspar	16	3	-	-
Gypsum	75	42	-	-
Mica (scrap)	15	7	-	-
Perlite	12	2	-	-
Phosphate rock	42	13	18	4
Potassium rock	7	1	6	-
Pumice	158	6	-	-
Salt	18	9	6	-
Sand and gravel	6,995	2,240	118	-
Sodium carbonate (natural)	3	-	3	-
Stone:[e]				
Crushed and broken	4,621	1,717	205	1
Dimension	405	-	-	-
Talc, soapstone, pyrophillite	51	3	-	-
Vermiculite	3	1	1	-
Other[f]	29	9	-	-
Total Nonmetals	13,967	4,233	360	5
Grand Total	14,437	4,331	419	21

---

[a] Excludes wells, ponds, or pumping operations.
[b] Data incomplete.
[c] Antimony, beryllium, manganiferrous ore, molybdenum, nickel, platinum-group metals, tin, and vanadium.
[d] Emery, garnet, and tripoli.
[e] Includes limestone (see text).
[f] Abrasive stone, aplite, graphite, greensand marl, iron oxide pigments (crude), kyanite, lithium minerals, magnesite, mica (sheet), millstones, olivine, and wollastonite.

TABLE V-5

PRODUCTION OF ORE IN THE U.S. BY MINING METHOD-1971 FOR THE MAJOR MINERAL COMMODITIES

(Thousands of Short Tons)

Material	Open Pit	Underground	Total	% Underground
Bauxite	2,709	W[a]	2,709	--
Copper	222,450	26,002	248,453	10.5
Gold	3,477	1,985	5,461	36.3
Iron Ore	206,412	12,678	219,091	5.8
Lead	<1	9,962	9,962	100
Mercury	156	120	276	43.5
Silver	29	710	739	96.0
Titanium-Ilmenite	21,525	--	21,525	--
Tungsten	22	641	663	96.7
Uranium	2,929	3,127	6,056	51.6
Zinc	156	9,007	9,163	98.3
Total Metals	459,865	64,232	524,098	12.3
Asbestos	2,373	W[a]	2,373	--
Barite	3,785	114	3,899	2.9
Clays	53,871	1,114	54,985	2.0
Diatomite	551	--	551	--
Fluorspar	58	691	749	92.3
Gypsum	8,022	2,298	10,319	22.3
Phosphate Rock	132,911	322	133,233	0.2
Salt	720	14,661	15,381	95.3
Sand & Gravel	919,608	--	919,608	--
Stone (inc. Limestone)	844,953	31,930	876,883	3.6
Total Nonmetals	1,966,853	51,130	2,017,981	2.5

---

[a] Information withheld to avoid identification of a sole producer.

The actual area in the mine where ore is removed is called a "stope." There are a wide variety of stoping methods with the principal ones being room and pillar, caving, and cut and fill. The method of stoping and access used depends upon the type of ore being mined and the geologic nature of deposit. Table V-6 shows the various underground mining techniques used for metal and nonmetallic minerals.

- Room and Pillar

  This system is similar to that used in conventional room and pillar coal mines. Typical extraction efficiencies for ore deposits are about 50%, but in many cases ore extraction can be increased to 70-80% by robbing pillars as is done in coal mining.

- Caving

  This method is used for large disseminated deposits. Access to the ore body is from below, and large blocks (hundreds of square feet) are undercut and induced to cave. Ore is then extracted through ore passes into haulage equipment below.

- Cut and Fill, Square Set, Open Stopes, Long Hole, Shrinkage

  These methods (and a number of others, as well as various combinations) are used for vein-type deposits where there is vertical or steeply dipping ore structure of limited width (3 feet to 30 feet wide).

  Cut and fill involves mining the ore and filling the empty spaces with broken waste rock or tailings from the milling operation. Square set stoping involves supporting the open spaces with timber. This method is no longer extensively used because of the high cost of timber and the labor to install it. Open stopes merely refers to mines left open where there is no need to fill.

  Long hole stopes are those where drilling is accomplished by a series of long (50-100 feet) holes from a series of access openings rather than drilling shorter (5-6 feet) holes every shift. These stopes can be filled or not as needed.

  Shrinkage stopes involve breaking the ore and mining upward in a stope working from the surface of the broken ore. Enough broken ore is withdrawn to provide working space. When mining is finished, the stope is full of broken ore, which is then drawn out. The final space open can be filled but is often left open.

TABLE V-6

GENERAL TYPES OF METAL AND NONMETAL MINES AS RELATED TO GEOLOGIC NATURE OF DEPOSITS

A. Underground Mines

1. Bedded - Flat Lying or Slightly Dipping - Sedimentary-Type Deposits:

Examples: Copper = Michigan
Lead, Zinc = Missouri, Tri-State District
Zinc = Tennessee, Washington
Uranium[a] = Colorado, New Mexico, Utah, Wyoming
Salt = Kansas, Louisiana, Michigan, Ohio, New York
Limestone = Iowa, Illinois
Gypsum = New York
Trona = Wyoming
Potash = New Mexico, Utah
Iron Ore = Missouri, Michigan, New York, Pennsylvania, Wyoming
Phosphate = Montana, Idaho

General Mining Procedure:

Access = Shafts, Inclines and Ramps, and Adits - On Level Mining
Haulage = Rail, Truck, Belt, Combinations of These
Stoping = Room and Pillar

2. Large Disseminated Ore Bodies:

Examples: Copper = Arizona
Molybdenum = Colorado
Iron Ore = Pennsylvania, Michigan, Missouri

General Mining Procedure:

Access = Shafts or Adits - Approach below Ore Bodies
Haulage = Usually Rail (Ore-thru-Ore Passes)
Stoping = Block or Panel Caving

3. Vein-Type Deposits - Wide and Narrow - Usually Dipping:

Examples: Gold = South Dakota
Silver, Copper = Idaho
Copper = Montana, Arizona, Tennessee, New Mexico
Lead, Zinc = Idaho, Utah, Colorado, New York
Silver, Copper = New Jersey, New Mexico, Montana
Fluorspar = Nevada, Kentucky, Illinois, Colorado, Montana
Mercury = California, Oregon, Nevada
Uranium = Colorado

General Mining Procedure:

Access = Shafts, Adits, Inclines - Both Hanging and Footwall Approaches
Haulage = Rail and Trackless
Stoping = Cut and Fill, Square Set, Open Stopes, Long Hole, Shrinkage

B. Open Pit and Surface Mines

Examples: Copper = Arizona, Nevada, New Mexico, Utah
Iron Ore = Michigan, Minnesota, California
Uranium = New Mexico, Wyoming
Phosphate Rock = Florida, Tennessee
Gold = Nevada

General Mining Procedure:

Access = Benches after Removal of Overburden
Haulage = Truck, Rail, Belts
Mining = Shovels, Front-End Loaders

---

[a] Uranium - Special case in this group with sub-level and on-level mines, random pillars, small scattered deposits, radon problem, etc.

Source: Arthur D. Little, Inc.

The major method of gaining access to underground ore bodies uses vertical shafts, which in the United States vary from about 200 feet in depth to nearly 5,000 feet. These shafts are usually rectangular or circular and are normally lined with timber, concrete, or steel.

These shafts usually have compartments or arrangements for communication cables, water power, and compressed air lines. Most shafts in metal mines service a number of levels where there are shaft stations. In flat-bedded sedimentary type deposits, only one horizon is generally mined so that the shaft services only one level.

Where the topography permits, horizontal or slightly dipping openings (adits) also are used as a means of access to ore bodies. Many mines in mountainous regions have combinations of shafts and adits for developing and working the ore body. Adits are of any reasonable size that allows space for the required vehicles and accessory items such as cables, pipe, and ventilation tubes. Adits can be several miles long.

Haulage ways are sized to allow adequate movement of men, materials, and ore haulage vehicles. Distances from the shaft can vary from about 400 feet to about 5 miles, depending on the type of mine and on how much it has been developed. Rail haulage is currently the most common mode of transportation in all underground mines, and it is not uncommon to have three or four trains operating at one time. In such situations, traffic control lights and systems are used. Increased use of trackless vehicles is replacing rail haulage in some new mines.

In vein-type mines the haulage distances are often less than those for caving mines. Usually, the shafts will be centrally located with respect to the ore body, and haulage will be on a number of levels going both ways from a shaft or shafts for several thousands of feet.

Some recent mining systems have gone to a trackless haulage system using LHD (load, haul, dump) equipment. Ramps are driven from the surface to connect all levels for easy access and flexibility of equipment usage. Ore is moved to ore passes and hoisted.

Open Pit Metal and Nonmetal Mining

The typical open pit metal or nonmetal mine or quarry is an operation that first removes overburden to reach the ore, then mines the ore and delivers it to a processing plant where processing takes place, resulting in a finished salable product and a waste for disposal.

Open pit mining is carried out by the major operations of drilling, blasting, loading, and hauling. Earth-moving equipment is used, such as shovels, draglines, front-end loaders, bulldozers, scrapers, and trucks. Conveyor belts are often used, as well, for haulage. A wide variety of sizes and makes of equipment are used. Much of the equipment is very large, that is, shovels up to 25-cubic yard capacity, draglines with up to 200-cubic yard buckets, and off-highway trucks up to 200-ton capacity. Overburden is moved out of the mine area and dumped in waste piles.

c. Capacity for Sludge Disposal in Metal and Nonmetal Mines

Since a 500-megawatt power plant can produce between 400,000 and 1 million short tons of wet sludge annually, a significant number of the mines shown on Table V-4 would easily have adequate ore extraction to provide capacity for sludge from one or more plants (assuming all the voids created were remaining and accessible). As Table V-5 indicates, few of the commodities listed could fully accommodate the estimated annual production of the nation's sludge. Most of the metal and nonmetal ore production is from open pit mines unsuitable technically for waste disposal. None of the commodities listed as employing underground mining techniques could individually accommodate all of the nation's FGD sludge in their active underground cavities.

Limestone mines are of particular interest, since all throw-away systems involve the use of limestone either directly or indirectly (through the use of limestone to manufacture lime). For this reason there is often a transportation network (rail and/or truck) that is in service or readily available for delivery of the limestone.

There are presently about 30 underground room and pillar limestone mines in 12 states with each mine producing over 300,000 tons of limestone per year. The total limestone production from these mines amounts to over 20 million tons annually. With the exception of one mine located in California, all of these mines are located in the Interior and Eastern regions (Oklahoma, Illinois, Kentucky, Ohio, Tennessee, Virginia, Kansas, Iowa, Missouri, and Pennsylvania). About half of this underground limestone

stone production is spread across the midsection of the country in four states--Kentucky, Illinois, Missouri, and Kansas.

A mine dedicated to providing limestone for use in FGD systems will not be able to handle all of the sludge produced from those systems. As a rule-of-thumb, roughly 1.2-1.4 tons of dry FGD sludge (without ash) are generated for every ton of limestone used. Including water, this sludge will require a volume for disposal more than three times that created by the limestone removal. Where only a fraction of the limestone produced in any mine is used in FGD systems, that mine could serve as a disposal site for all of the FGD sludge generated from the limestone.

3. Screening of Mine Disposal Options

The purpose of this report is to assess the feasibility of FGD sludge disposal in mines, but clearly not all the different mine environments can be addressed. There are thousands of mines throughout the United States, and each one is different in some respect. However, they can be grouped by region, mineral mined, mining method, and size; impacts can be assessed for conditions deemed average for the various mine groupings. Therefore, in order to focus on the most promising alternatives, we have grouped mines according to region and mineral mined and have ranked these groups of mines for their technical feasibility. Those mine options selected as most promising technically are described and assessed for environmental impacts in the following sections of this report.

Technical criteria were used to screen mines because of ease of grouping mines by technical factors (location, mining method, disposal method, and capacity) versus grouping by environmental factors (hydrogeology, water resources, biota) and because the inclusion of environment criteria in the mine selection would impose predictive value judgments on the outcome of the environmental assessment. The mining methods included were: surface area and contour strip mining, underground room and pillar, underground longwall, underground cut and fill, open pit, and quarry mining. Sludge placement methods included hydraulic slurry pumping, pneumatic stowing, and truck dumping.

A ranking system to choose the most promising types of mines inherently involves value judgment based on professional experience and literature review. We expect there will be individual mines, within the mine groups considered least promising, which will provide a worthy local disposal site. However, our ranking is derived from a national perspective and does not consider small mines having site-specific favorable conditions.

For categories of mining commodities and mining methods, disposal feasibility is ranked according to the limitations below:

- probably limited capacity;
- difficult handling or placement of sludge; and
- prevention of future resource utilization due to sludge placement.

A category of mining is not considered a promising solution to the nation's projected sludge disposal needs if it typically has one or more of the above limitations. Tables V-7 and V-8 rank the mine options. Rating of the mine options is as follows:

1. promising for FGD sludge disposal;
2. may be promising for FGD sludge disposal;
3. of doubtful promise for FGD sludge disposal; and
4. not promising for FGD sludge disposal.

a. Coal Mine Screening

From Table V-7 it is apparent that active coal mines are generally favored as more technically promising than inactive coal mines. The opportunity for sludge disposal in inactive coal mines depends on site-specific local situations.

Unreclaimed inactive and depleted surface mines usually consist of the final strip pit (which is often filled with water) and a series of ridges of overburden. Sludge placement would require extensive earth movement. Ownership and responsibility for the mine may be dubious, and sludge placement costs would probably require governmental sponsorship. Reclaimed surface mines by definition do not have any capacity for FGD sludge disposal.

Old and inactive underground coal mines are often caved and filled with groundwater of unknown flow patterns caused by the hydrogeologic changes created by mining. The voids are difficult to find because of prior roof collapse as pillars deteriorated and failed; even the initial open

TABLE V-7

COAL MINES

SCREENING FOR ACCEPTABILITY FOR FGD DISPOSAL

	Underground				Surface Mines			
	Inactive		Active		Inactive		Active	
	R&P	L.W.	R&P	L.W.	Contour	Area	Contour	Area
Lignite:								
Eastern	–	–	–	–	–	–	–	–
Interior	–	–	–	–	–	4	–	2
Mountain	4	–	4	–	–	4	–	2
Bituminous:								
Eastern	3	4	2	2	4	4	3	3
Interior	3	–	2	–	–	4	–	1
Mountain	3	4	3	2	–	4	–	1
Anthracite:								
Eastern	3	–	4	–	3	–	3	–
Interior	–	–	–	–	–	–	–	–
Mountain	–	–	–	–	–	–	–	–

R&P = Room and Pillar

L.W. = Longwall

Note: Numbers refer to ratings described in text.

TABLE V-8

METAL AND NONMETAL MINES

SCREENING FOR ACCEPTABILITY FOR TSD DISPOSAL

Ore Type	Underground		Open Pits		Pits & Quarries	
	Inactive or Abandoned Portions-Active	Active	Inactive	Active	Inactive	Active
Metal Ores						
Bauxite	4	4	4	4	–	–
Copper	4	4	3	4	–	–
Gold	4	4	4	4	–	–
Iron Ore	3	4	3	4	–	–
Lead	2	3	4	4	–	–
Mercury	4	4	4	4	–	–
Silver	4	4	4	4	–	–
Titanium	4	4	4	4	–	–
Tungsten	4	4	4	4	–	–
Uranium	4	4	4	4	–	–
Zinc	2	3	4	4	–	–
All Others[a]	4	4	4	4	–	–
Nonmetallics						
Sand and Gravel	–	–	–	–	4	4
Stone:						
Limestone	2	4	–	4	3	4
Others (Granite, Traprock, etc.)	4	4	–	–	3	4
Phosphate Rock	4	4	4	4	–	–
Salts	2	4	–	–	–	–
All Others[b]	4	4	–	–	4	4

---

[a] Antimony, beryllium, moly, nickel, Pt. group, tin, vanadium, rare earths.

[b] Asbestos, abrasives, barite, boron, clays, diatomite, feldspar, fluorspar, gypsum, mica, perlite, potash, pumice, talc, soapstone, vermiculite, pigments, kyanite.

cavities (before roof collapse) are difficult to delineate, as underground mining plans were generally not submitted. Only under local conditions, such as those prevalent in the anthracite region of Pennsylvania, might sludge placement in abandoned underground mines be justified to limit acid drainage formation and surface subsidence damages.

Active surface area coal mines in the Interior and Western regions receive the highest ranking as technically promising for sludge disposal because of their individual capacity (assuming sludge disposal occurs simultaneously with extraction and reclamation) and the ease of sludge placement within existing operations. The Eastern surface mines are generally considered less promising because they individually are much smaller mines. Also, the Eastern contour mining allows less ease of sludge placement than area stripping.

While the active underground coal mines show technical promise for accepting FGD sludge, they are not considered as promising as the active surface mines. Sludge placement would add complication and additional maneuvering to the already difficult working conditions. Also, many of the underground mines mix techniques of conventional room and pillar with pillar robbing and/or longwall mining within one mine and would therefore require more than one method of sludge placement and range of sludge properties.

b. Metal and Nonmetal Mine Screening

Of the active metal and nonmetal underground mines, only the room and pillar operations on relatively horizontal seams are viable (see Table V-6). Copper, iron ore, lead, zinc, salt, and limestone are mined in substantial quantities by underground room and pillar methods. Other methods of underground mining, such as caving and cut and fill, leave little available void for sludge disposal. A small amount of sludge might be mixed with sandfill and introduced into stopes of mines employing fill; however, these amounts are not considered substantial enough to rank these mine categories as promising to provide solutions to the pending national sludge disposal needs. Underground mining of precious metal, such as gold and silver, which often occurs in steeply dipping deposits, may not employ fill; however, FGD sludge disposal would discourage the future mining of the deeper vein segments left in place.

Of the active underground metal mines, only lead-zinc mines show promise for sludge disposal by our ranking system. These lead-zinc mines have about 70% of the ore extracted after room and pillar mining and pillar robbing (called slabbing); the void space after ore extraction generally remains open and accessible. Also, because of the high extraction percentage, it is doubtful that these mines would be reopened for further exploitation.

Of the active underground nonmetal mines, limestone and salt room and pillar mines show promise. There are about 30 active underground room and pillar limestone mines with substantial capacity for sludge placement. Some of these are dry hillside mines with thick mine seams (averaging 40 feet thick). And there is easy access for dry FGD sludge dumping. About 60% of the ore is removed by the room and pillar method, with the remainder left as pillars for roof support. Because of the thickness of the seam (up to 100 feet thick), roof collapse could create substantial subsidence at the surface. Therefore, it is doubtful that future pillar robbing would occur and that FGD sludge disposal would be significant to future resource recovery.

There are about 16 active room and pillar salt mines annually producing about 18 million tons per year in total. Room and pillar salt mines are dry. Even though below the water table, their shafts are carefully sealed to prevent water entry. Extraction of 60-70% of the salt is normal, with the remainder left as pillars. Since these mines are not caved and are accessible, placing moist to dry sludge would be feasible. Placement of wet sludge would generally not be practical because it could dissolve salt in the pillars, allowing them to weaken and possibly result in roof collapse. Site-specific assessment would be required to determine the viability of placing wet sludge. The published literature contains an assessment of waste disposal in underground salt mines (1).

Active open pit metal and nonmetal mines, while abundant and individually large voids, are not considered viable FGD sludge disposal sites because of the nature of mining. Generally, overburden is removed from the mine area and the mineral mined downwards from the surfaces in benches. For example, small amounts of copper are deposited in porous strata about 1,000 feet thick, and the ore is mined in concentric circular benches from the surface. Because of the nature of mining, neither overburden nor tailings are returned to the pit during the life of the mine. These open pits are not normally reclaimed, as shown in Table V-1. In the case of some active iron ore open pit mines, mining advances down-dip along the ore seam. It may be possible to construct impoundments to isolate the mined-out portion for FGD sludge disposal; however, such impoundments would block access from the surface to the working faces. Therefore, the category of open pits is considered generally unpromising.

There is no readily available information on the location and condition of inactive or depleted mines, either open pit or underground. In some cases, these are closed for economic reasons linked to market demand and many be reopened for additional recovery of valuable material. It is believed that most of the abandoned mines are closed for economic reasons and that few are fully depleted. There are probably three or four finished open pit metal mines in Arizona, several in Nevada, Utah, and Montana, and six or seven in the iron ore regions of Minnesota and Michigan. These often form manmade lakes where water sport recreation develops. Most abandoned underground mines have been stripped of all timber and equipment and are not easily accessible. These underground mines might be large in total tonnage but individually are expected to have limited capacity. Only the old lead-zinc underground mines of southeast Missouri and the limestone underground of the Midwest appear to provide a large capacity for sludge and to have remained largely intact (not caved).

On the basis of the above discussion, mine cases selected for impact assessment because of technical feasibility are:

- surface coal mines - active;
- underground coal mines - active;
- underground lead-zinc mines - abandoned or mined-out portions of active; and
- underground limestone mines - abandoned or mined-out portions of active.

B. DISPOSAL OF FGD SLUDGE IN SURFACE COAL MINES

1. Range of Conditions Possible

There are three types of active surface coal mines showing promise for the disposal of flue gas desulfurization sludge. Based on the technical considerations previously discussed, Interior and Western surface area coal mines show the greatest promise; Eastern surface contour coal mines show less promise due to their lower indiviudal capacity and the greater difficulty of sludge placement.

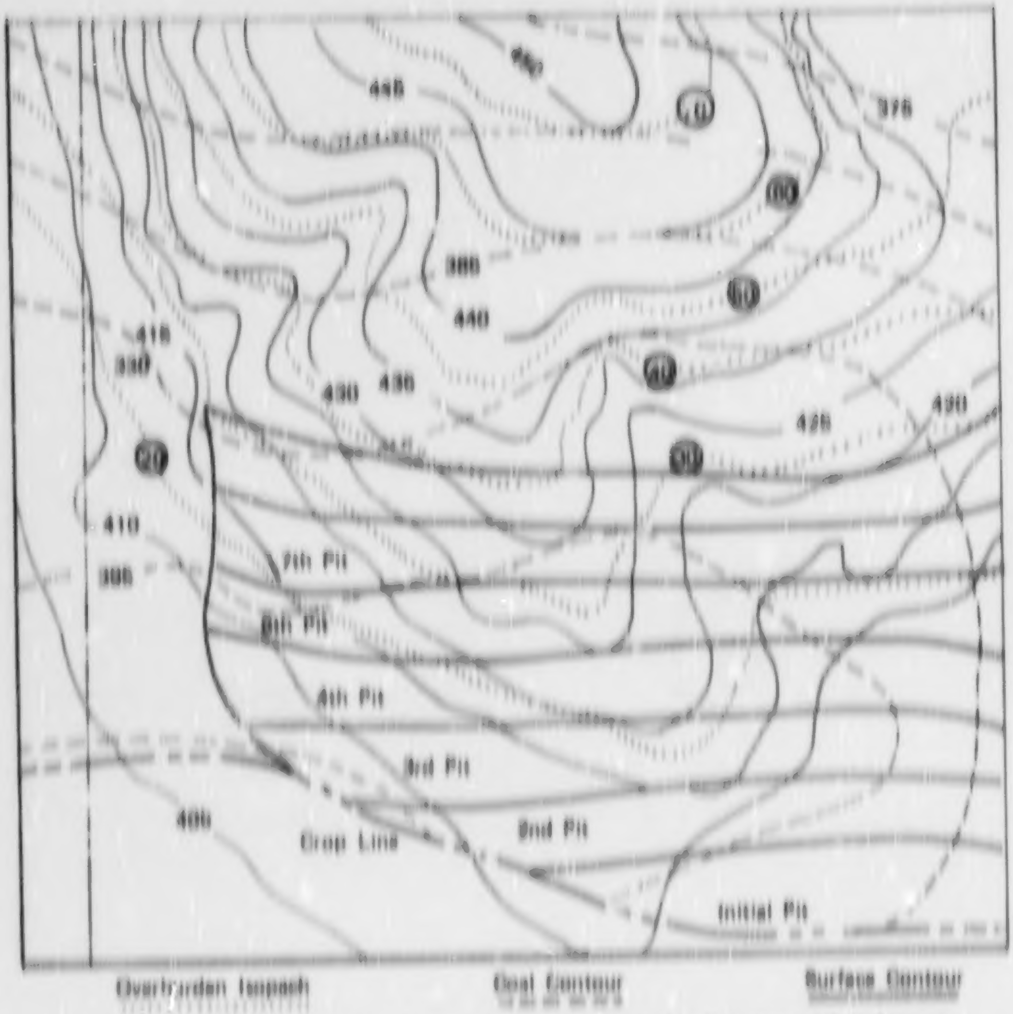
Each coal mine is unique. Its operation, hydrology, geology, groundwater, and soils characteristics are necessarily different from those of any other mine. However, in order to assess impacts of FGD sludge disposal in mines, general conditions have been chosen that are believed to be average for a given type of mine and region of the United States. By comparing a site-specific mine with the conditions we define as average, site-specific impacts may be extrapolated from this report.

A. Interior Surface Area Coal Mine

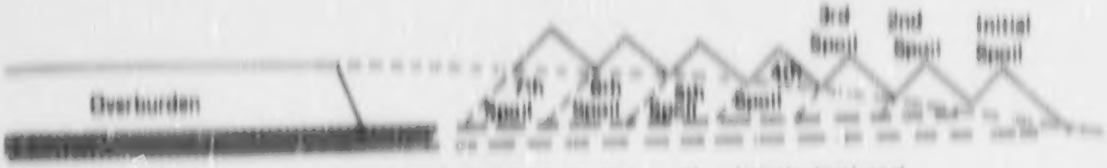
Coal production from an Interior surface area coal mine ranges between 0.1 and 6.5 million short tons annually. Coal is mined from seams varying in thickness between 2.5 feet to 7 feet. Depth of overburden material to be stripped before the seam is extracted varies from a feather edge at the seam outcrop to about 120 feet. The dip of the coal seam ranges from horizontal to about 5 degrees.

The average interior surface mine produces about 1.5 million short tons of coal annually as a washed product (1.9 million short tons are removed from the mine, and washing wastes are returned). The principal coal seam mined is 6 feet thick and covered with about 85 feet of overburden bedrock and soil. The coal seam is bounded by relatively impervious underclay or shale, with most of the overburden rock being limestone. The soils in the Interior region vary widely; often they are clayey (resulting in little natural leaching) and therefore high in bases. Overburden, which is moved and later placed on the sludge, will be a mixture of soil and broken rock materials as well as some coal particles.

An Interior surface area mine averages reserves of 30 million tons and has a life of 20 years. This allows the coal seam to be stripped in six 90-foot wide cuts each year. A typical pit length is two miles. Mining operations begin where the coal outcrops or is closest to the ground surface and continues with pits running perpendicular to the seam dip. Figures V-7 and V-8 illustrate mining operations and cross-sectional dimensions of a mine.


450
445
375
380
440
415
330
430
435
425
430
410
395
7th Pit
6th Pit
4th Pit
3rd Pit
400
Crop Line
2nd Pit
Initial Pit
Overburden Isopach
Coal Contour
Surface Contour

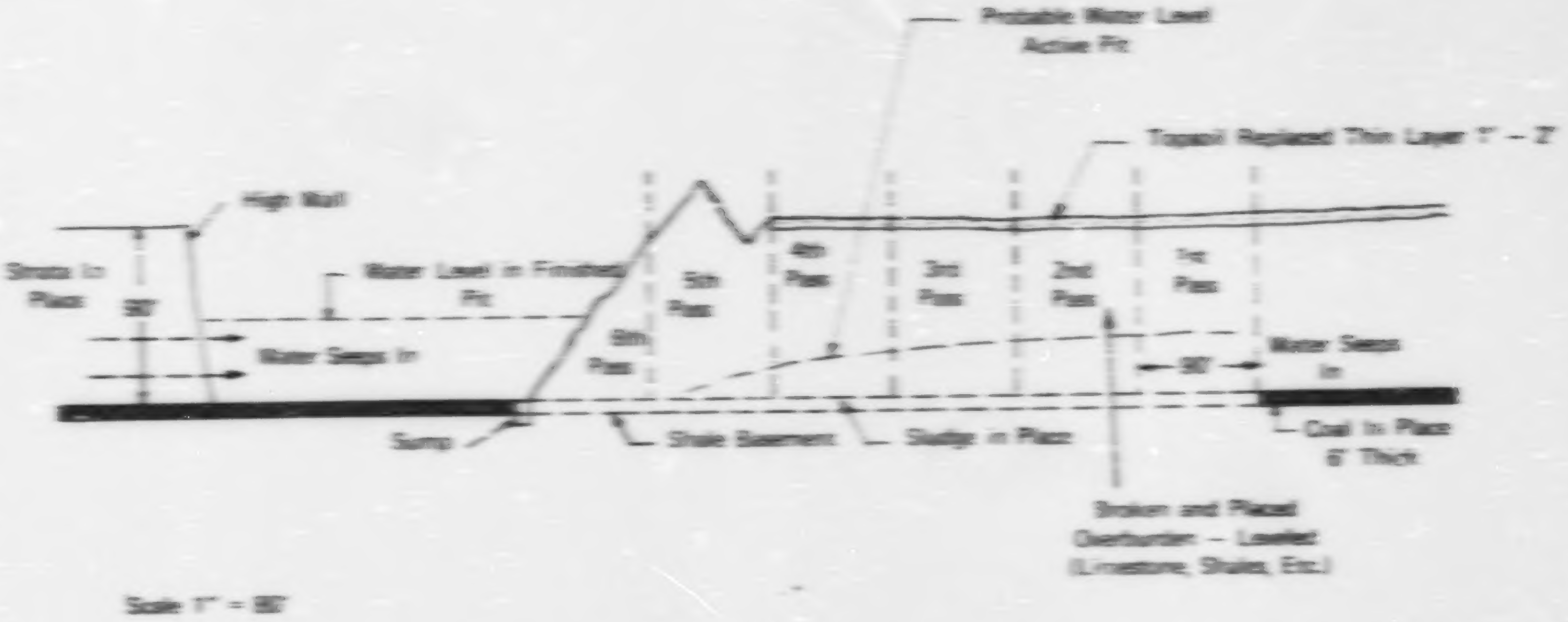
Projection of cuts in a surface mine. In this case both the coal seam and surface are relatively level.


3rd Spoil
2nd Spoil
Initial Spoil
7th Spoil
6th Spoil
5th Spoil
4th Spoil
Overburden

Typical cross section of an "area" surface mining operation with relatively level coal and surface.

Source: Cassidy, S.M., *Elements of Practical Coal Mining*, Society of Mining Engineers, New York, 1973.

FIGURE V-7 AREA COAL STRIPPING



Probable Water Level
Active Pit
Topsoil Replaced Thin Layer 1" – 2'
High Wall
Strata In Place
90'
Water Level in Finished Pit
Water Seeps In
6th Pass
5th Pass
4th Pass
3rd Pass
2nd Pass
1st Pass
90'
Water Seeps In
Sump
Shale Basement
Sludge in Place
Coal In Place
6' Thick
Broken and Placed
Overburden – Leveled
(Limestone, Shales, Etc.)
Scale 1" = 80'

FIGURE V-8 CROSS SECTION – OPERATING STRIP COAL MINE

In the Interior coal region, power plants are in relatively close proximity to coal mines. A large mine could conceivably handle FGD sludge from more than one power plant. For high-sulfur coal, roughly twice the quantity of sludge (including ash) produced from the coal mined could be returned to the pit (assuming coal refuse tailings comprising about 25% of the quantity of coal removed were also being returned to the pit). A small mine, which supplies only part of a utility's coal requirements, therefore, might be contracted to handle all or part of the FGD sludge from one power plant. For the above example of an Interior mine producing 1.5 million short tons of coal yearly (after separating the coal refuse) approximately an equal volume of sludge could be returned, up to 2.0 million tons of compacted sludge.

In the area of the Interior region where most of the surface area mining occurs the climate is moderately wet. Precipitation ranges from 32 to 42 inches annually, with annual runoff ranging from 7 to 12 inches.

While it is not possible to specify the geology which may be encountered in a specific mine, the following generalizations prevail in the most actively mined portion of the Interior coal region (especially southwest Illinois). The area consists of plains underlain by gently dipping consolidated bedrock formations. The overburden consists of a thick layer of clayey soil of low groundwater yield; only river valley alluvium yields significant groundwater. The soil portion of overburden is typically underlain by limestone which provides low to moderate groundwater yields for local water supplies. Below the coal seam and its abutting underclay or shale, limestone and sandstone strata commonly provide moderate yield of public water supply. The bedrock dips gently, while the surface plains undulate with a prevailing dip to where the coal seam outcrops. The regional groundwater flows in the direction of surface drainage; however, in the active portions of a mine, groundwater flow may be controlled by other factors, i.e., impervious strata underlying the extracted coal seam.

Mine drainage in this region is usually neutral to alkaline. This may be attributed to one or more factors. For example, the coal seam may be low in the types of pyrite (especially framboidal pyrite) believed to cause acid drainage upon exposure to air and water. The prevalence of limestone in the overburden causes a very alkaline background groundwater which may neutralise acid drainage if and when it forms.

b. Western Surface Area Coal Mine

The production of coal from Western mines ranges from 0.6 to 6.8 million short tons annually. As methods improve to extract the wide seams prevalent and to mitigate environmental degradation, this production will increase. Seam thicknesses in the Western region range from 4 feet to 100 feet thick. Overburden depth ranges from a feather edge at the seam outcrop to about 125 feet at the point where surface stripping is currently halted. The seam dip varies from horizontal to as much as 10 degrees. Most of the seams dip downward from the outcrop and into an underground basin.

The most prevalent Western surface area mining conditions include large production from the outcrop of thick, moderately to steeply dipping seams, such as the Hannah seam in Wyoming. Therefore, for the average mining scenario a Western surface coal mine produces about 6.0 million short tons of coal per year from a 70-foot thick coal seam overlain with 30 feet of overburden. The rock overlying the coal seam includes a sequence of sandstone, siltstone, shale, and limestone. The soil mantle is thin. Soils are sandy, with some clay and silt, and low in organic matter. The soil layer ranges from 5 to 15 feet deep and usually is basic.

The subbituminous coal reserves in the State of Wyoming exceed 13.0 billion tons. The reserves of each mine depend upon the acreage owned by the mining company and the economic limits set by overburden depth. Typically, a mine operates on two benches with shovels and trucks. About 100,000 tons of coal are mined per acre, and 44 acres are mined yearly. Figure V-9 shows a cross-section of average conditions for a mine.

A Western mine may be producing for a mine-mouth plant or for one or more remote plants linked by unit train. If all of the sludge (including ash) produced from the subbituminous coal is returned to the mine, there would be about 0.25 tons of FGD sludge with fly ash (50% moisture) returned for every ton of coal removed. Therefore, for a mine producing 6.0 million short tons of coal per year about 1.5 million short tons of sludge would be returned for disposal. This sludge would fill roughly 20-30% of the void created by coal extraction.

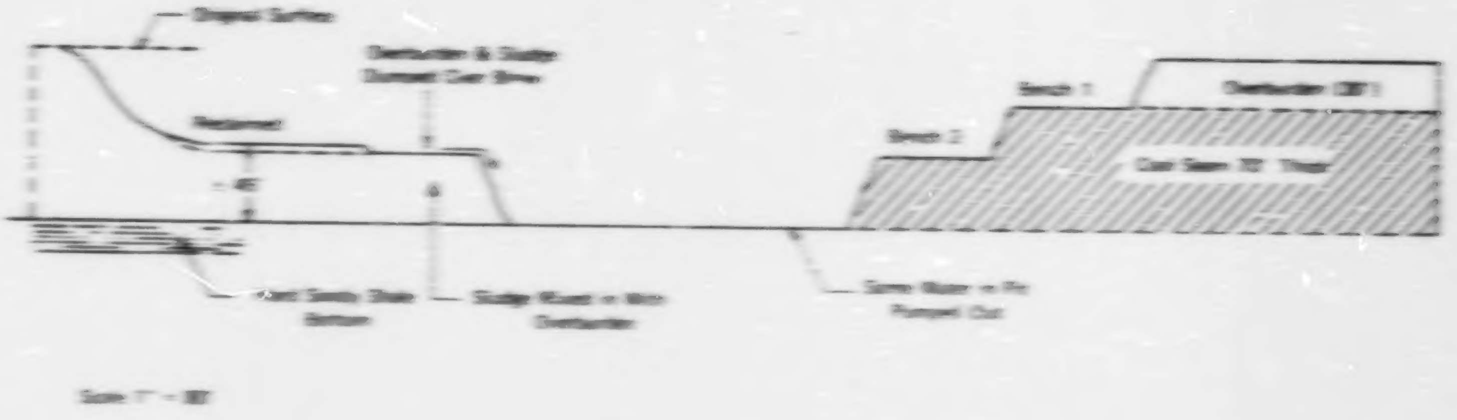

Original Surface
Overburden & Sludge Dumped Over Brow
Reclaimed
~ 40'
Hard Sandy Shale Bottom
Sludge Rises in Wet Overburden
Some Water in Pit Pumped Out
Bench 1
Bench 2
Overburden (30')
Coal Seam 70' Thick
Scale 1" = 80'

FIGURE V-8 CROSS SECTION – WESTERN STRIP MINE

The geology of each mine varies. However, for the area within the Western coal region where most of the surface mining currently occurs (namely, Wyoming) some generalized conditions prevail. The area is water poor. Precipitation ranges from 8 to 24 inches annually, and runoff ranges from less than 1 inch to as much as 20 inches. The high runoffs are indicative of the flash flooding characteristic of semi-arid areas. Groundwater recharge is low, as low precipitation and high runoff couple with significant evapotranspiration loss to result in little percolation. Within the coal mining areas, groundwater is found mostly in the bedrock units of sandstone and coal.

There is little acid drainage in the area. The environment does not provide the optimum acid formation conditions of oxygen coupled with high humidity. Also, while there is not an abundance of limestone in this region, the soils are basic (because the dry conditions have allowed limited leaching of the salts) and resulting groundwaters have significant buffering capacity. Finally, there may be a limited amount of reactive pyrite.

c. Eastern Contour Strip Mine

Contour strip mines occur where coal seams outcrop on hillsides. These mines are principally located in the Eastern coal region. Collectively, their production compares with Interior and Western mines. However, the production of coal from individual Eastern contour strip mines is generally less than from individual Interior or Western strip mines (compare Tables V-2 and V-3). The production of an Eastern surface contour mine varies from about 0.01 to 1.5 million short tons. The coal seam thickness ranges from about 2.5 feet to 7 feet. Overburden depth ranges from nil at the hillside outcrop to 100 feet at the final pit. Most of the seams are nearly horizontal; however, there are slight dips or undulations that slope as much as 10 degrees. An average surface contour mine produces about 0.4 million short tons of coal annually. The coal seam is about 6 feet thick, with overburden up to 120 feet thick. In a contour mine with a finished pit it is common practice to recover more coal by augering into the seam.

In the average contour strip mine case, the approximate dimensions mined annually are 565 feet by 2,840 feet (37 acres). If the hillside slope is about 12 degrees or less, a "contour" backfill, as illustrated in Figure V-10, can be used. In this case, the highwall is completely covered and the area is reclaimed to the approximate original topography. Where surface slopes are steeper than 12 degrees, a "terrace backfill" is often used; the highwall is cut back and pushed into the pit and a terrace is left on the hillside. Backfilled overburden consists mostly of broken rock from hillside sandstone and shale outcroppings.

Many power plants in the Eastern coal region are in close proximity to the coal mines. Since most of the Eastern surface coal mines are small producers, they would probably accept sludge from only one power plant. An Eastern mine producing about 0.4 million short tons of coal annually (after coal preparation) could accept an approximately equivalent volume of sludge, weighing up to 0.5 million short tons.

In the Eastern coal region most of the surface contour mining occurs in western Pennsylvania and eastern Ohio. From west to east the area becomes increasingly wet. Precipitation ranges from 30 to 48 inches, and runoff ranges from 10 to 30 inches. The geology of this region is very complex. Aquifers are difficult to locate. Coal seams and other rock strata at high elevations in the Appalachian plateaus are nearly horizontal and unaltered. Groundwater recharge and availability in the plateaus are limited, while groundwater yields are plentiful in the valley alluvium. In the plateaus, small to moderate yields come from limestone and sandstone aquifers.

Soils in this area are low in bases, largely because the humid environment has led to excessive leaching of salts from the soil mantle. This, coupled with the limited existence of limestone strata, leads to groundwater with little or no buffering capacity. Acid mine drainage in the area is substantial for a number of reasons; the pyrite in the coal is often of the acid-forming variety, the coal exposure to air and high humidity encourages acid formation, and the low buffering capacity of background groundwater cannot neutralize the drainage once it has formed. As the acidity of the drainage increases, microorganisms which thrive in low pH environs markedly catalyze the reactions.

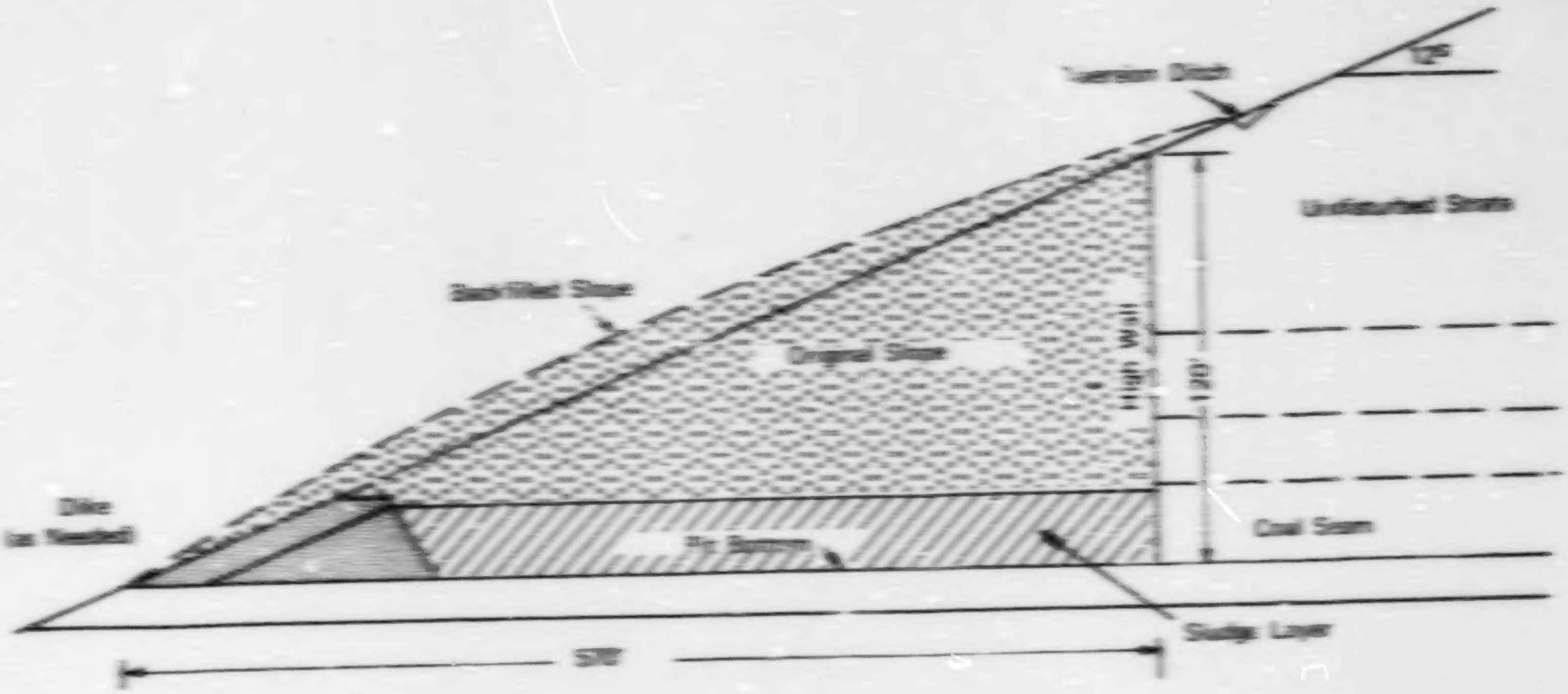

Diversion Ditch
12°
Undisturbed Strata
Backfilled Slope
Original Slope
High Wall
120'
Coal Seam
Dike (as Needed)
Pit Bottom
Sludge Layer
570'

FIGURE V-18 CONTOUR BACKFILL

2. Impact Assessment

As a basis for the assessment of sludge impact, we assume that in all three surface mine cases, disposal would involve placing the sludge by rear-dump trucks in the mined-out portion of the strip before returning overburden (or as overburden is returned to the pit in mines whereas haulback mining is practiced). Placing the sludge in the pit before overburden is returned is the easiest mode of disposal and will have the least disruptive effects on existing mining operations. Other methods of disposal are considered control techniques which mitigate adverse technical or environmental impacts.

a. Technical/Physical Impacts

Sludge Physical Constraints

In operating strip coal mines, overburden is moved with draglines, shovels, or bucketwheels and then the coal is mined with front end loaders, shovels, and trucks. The coal mining and hauling equipment and maintenance and supply vehicles all operated on the floor of the pit and on roads down into the pits. For efficient operation, pit bottoms and roads must be in reasonably good condition and are maintained with road graders, etc.

Mining operations could not continue effectively if the sludge flowed or acted like a mud when placed in the pit. The sludge has to be such that it can be placed by a rear-dump truck and covered with overburden without it spreading or squeezing out and flowing. It should also have some stability when rewetted (by precipitation) and should not flow under such conditions. It does not need to be of such strength that it will support mobile equipment, since it can be placed and covered without equipment running directly on it. In order for untreated FGD sludge to meet the above conditions for strip mine placement, it should be filtered or centrifuged and possibly admixed with fly ash. It should be immediately placed in the pit and covered with overburden or inventoried in stockpiles protected from rain. If left in open stockpiles, there is some potential for the material to erode when it rains.

Laboratory studies indicate that FGD sludges vary in compacted dry density from about 80-100 lbs/cubic foot after Standard Proctor compaction. If left uncovered or unmixed with overburden, sludge of these densities would be a poor foundation material and would not support traffic.

Furthermore, it is doubtful that truck dumping of loose FGD sludge and consolidation under the static loading of replace overburden would allow optimum compacted densities to be achieved in the field.

Groundwater returning to its original water table elevation in the reclaimed land areas of the mine may saturate the sludge. Even when placed in a loose state and saturated, the fine grained sludge is not expected to be liquefiable because of the overlying confining pressures of the replaced overburden. At the outcrop (especially of an Eastern contour mine) where the overburden depth is small, a dike should be designed and constructed to retain the sludge under applicable seismic loadings.

The amount of sludge handled in any surface mine should not exceed the amount of coal removed (by volume) for several reasons. First, the objectives of strip mine reclamation include returning the mined terrain to topographic configurations similar to the initial terrains. Second, the overburden and sludge are unconsolidated upon return, and even addition of the same weights will result in a thicker mass. Third, returning significantly more sludge to a mine than the coal extracted could slow down the simultaneous mining and reclamation activities.

Sludge dumping can be adapted to allow mixing of the overburden and sludge. In contour strip mines where haulback methods are used, there will be some mixing of sludge and overburden. In such mines, mixing may be accomplished with minimal impact on the operation of the mine. However, in most strip mines, mixing requires more handling (such as by the dragline or shovel) than may be readily acceptable to mining management. Since mixing with overburden may result in some soil attenuation of solute contaminants in the sludge, it is addressed in the discussion of control techniques.

Handling and Placement

Sludge would be most easily placed in the mined-out pit by truck dumping, but it is not recommended that coal haulage vehicles be used for sludge transport and placement. In some mines where rear-dump type trucks are used, sludge could possibly be transported by the existing coal haulage trucks on their return trip from the coal washing plant to the pit. However, such an operation may not be cost-effective, since the turn-around time for coal transport would undoubtedly increase due to the time required for loading and dumping sludge. Some sludge would also get mixed in with the coal, unless the sludge releases easily from the trucks. Since the coal is washed, a small amount of contamination can be tolerated, but any significant amount of contamination would necessitate cleaning the trucks, creating a delay.

Furthermore, most mines are now using large, bottom-dump trucks for coal haulage. While many trucks are designed to carry up to 100 tons of coal, they are lightweight with bodies usually constructed of aluminum. Not only could the sludge corrode the aluminum, but the bottom dumping of sludge would also be technically impractical. These types of trucks are not designed for ease of maneuvering in mine pits, and operating these trucks on a layer of sludge would be practically impossible.

Congestion in the working pit may result from the use of two-truck transport systems--one for sludge and one for coal haulage. Careful consideration needs to be given to general scheduling of coal/sludge transport as well as mining and reclamation activities in order to minimize inefficiency and lost productivity.

Additional technical impacts which may result from sludge disposal include potential dust problems if the fine grained sludge is allowed to dry when stockpiled, slide potential if the sludge is saturated when stockpiled, and erosion potential from storm runoff. These impacts can be minimized by disposing sludge in the same continuous manner in which coal is mined, thereby lessening the need for large sludge stockpiles. Chemical treatment of sludge would also lessen the potential for structural instability.

Although equipment exists at power plants for emptying coal cars, storing coal, and sometimes heating unit trains under freezing conditions, no such equipment exists at the mining end of the train operation to handle sludge. Sludge disposal would likely require a capital expenditure for sludge handling and transfer. Special handling may also include washing of the unit trains which might transfer sludge from the power plant to the mine before these cars could be filled with coal for their return trip. Delays due to increased handling and transfer procedures at the mine are expected to increase the overall costs at the mine.

FGD sludge disposal is not expected to impact on mine reclamation operations. In fact, partial filling of the mine void will help to allow reclamation to original topographic conditions. Coarse coal refuse from processing operations is already returned to the pit in most modern operations. FGD sludge disposal would parallel the coal refuse disposal operation.

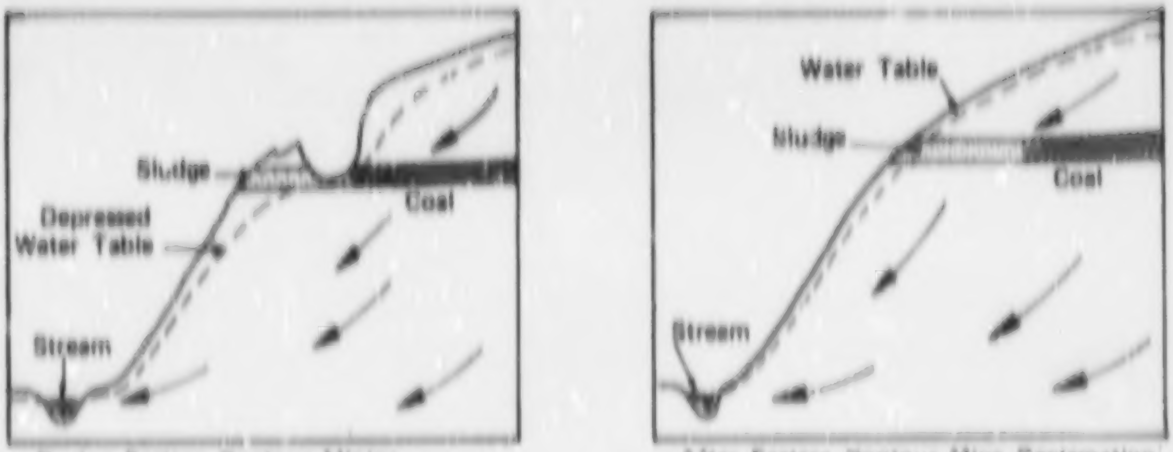
b. Environmental Impacts

Sludge Leachate

FGD sludge disposal is expected to contaminate contacted groundwater for hundreds to thousands of years in any surface coal mine disposal case. The extent of the effect and its acceptability can only be determined on a site-specific basis. The following discussion provides an overview assessment of relative impacts among Eastern, Interior, and Western surface coal mines as well as some basis for future assessments of specific FGD sludge disposal proposals.

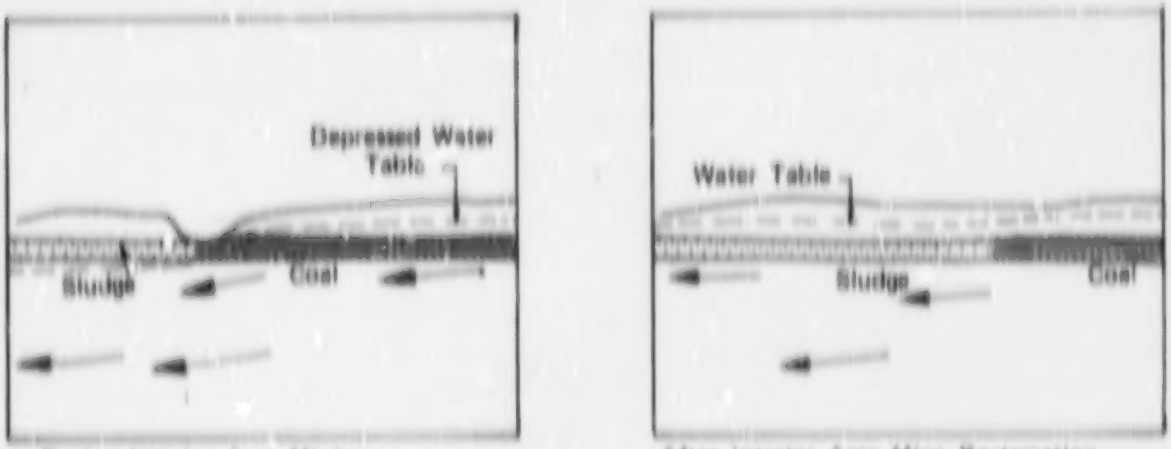
Leachate production is equivalent to the amount of percolation and groundwater underflow passing through the dicposed sludge. During mining and disposal the groundwater table is depressed, as needed, by pumping to keep the working area dry. Therefore, percolation is the dominant cause of leachate production in the vicinity of the working area. Once the working area is sufficiently removed from sludge disposal so that the initial water table is reestablished, groundwater underflow (saturated zone below the water table) becomes the dominant cause of leachate production, provided sludge disposal is below the water table.

Locally, underground hydrology may vary widely. Regionally, certain generalizations about the underground hydrology can be developed for the regional water balance (including factors of precipitation, evapotranspiration, and runoff) and the surface topography. Figure V-11 depicts the generalized movement of regional groundwater during and after surface mining of coal seams in the Eastern, Interior, and Western regions. As shown, pumping during mining alters the groundwater regime and may remove underflow from the sludge disposal. Once mining is completed in the sludge disposal area, the groundwater underflow essentially resumes its former flow configuration. The percolation rate is locally increased due to the disturbance and haphazard replacement of the overburden; however, the regional underflow rate is relatively unaltered.


Sludge
Depressed Water Table
Coal
Stream
Water Table
Sludge
Coal
Stream

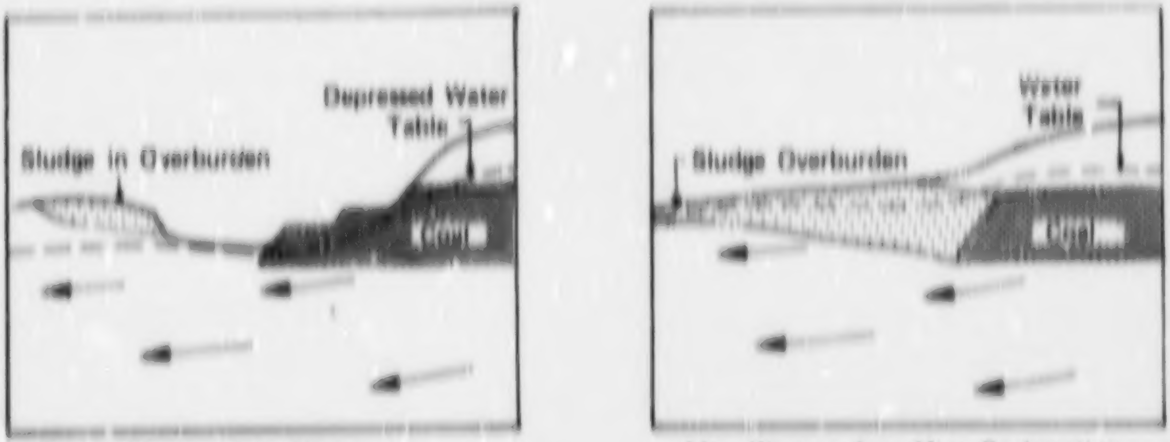
During Eastern Contour Mining

After Eastern Contour Mine Reclamation


Depressed Water Table
Sludge
Coal
Water Table
Sludge
Coal

During Interior Area Mining

After Interior Area Mine Reclamation


Depressed Water Table
Sludge in Overburden
Coal
Water Table
Sludge Overburden
Coal

During Western Area Mining

After Western Area Mine Reclamation

FIGURE V-11 REGIONAL GROUNDWATER MOVEMENT IN SURFACE COAL MINES

Since groundwater is derived almost entirely from precipitation, seasonal variations occur. The water that does not become runoff, or escape through evaporation and transpiration, percolates into the reservoir of groundwater. Typically, water levels are highest in the spring and lowest in the late fall. Snow melt and spring rains recharge groundwater. And since plants draw heavily on soil water during the summer, percolating water is removed before it reaches the groundwater underflow, and the water table lowers. As a result, the coal seam may be within the groundwater regime for only a portion of the year.

In Figure V-11 the mine cases are shown under the worst case condition, where the undisturbed water table is largely above the initial coal seam and subsequent sludge layer. This may not be the typical condition for the Eastern mine because the steep surface slopes and thin soil overlying the bedrock result in high runoffs and little percolation. This may also not be the case in the Western mine, where there is almost no groundwater recharge. The Interior mine, on the other hand, occurs in a moderately wet climate having gently sloping plains allowing time for percolation into the thick soil mantle.

Most surface mining advances downdip or horizontally from the outcrop or the lowest depth of overburden. As the mining continues, the water table is depressed more with each successive working pit. Sludge placed in the initial pits may therefore remain above the water table during mining. And, as mentioned, the primary means of leachate generation is percolation of rainfall through the overburden and sludge layers (or sludge/overburden mixture in the Western case). Most of the leachate would probably flow locally to a collection sump in the active mining pit. Minor amounts would flow into the regional groundwater underflow.

Leachate collected in the working pit with the background mine drainage would add to the contaminant level of the discharge. Since mine drainage collected and pumped from the working pit must meet EPA recommended effluent guidelines, wastewater treatment of the drainage may be required before discharge. Parameters limited by effluent guidelines for coal mine discharge are iron, aluminum, manganese, nickel, zinc, and total dissolved solids.

During mining, relative impacts for each of the surface coal mine cases would vary according to:

- the amount of leachate due to percolation;
- the dilution of leachate due to surface runoff and collected groundwater in the mine water drainage; and
- the leachate contaminant level as affected by the composition of the replaced overburden and background quality of the mine drainage.

For the Eastern case where precipitation is the greatest, leachate generation from percolation through overburden will be significant. Surface runoff from the steep slope above mining will provide substantial dilution. Since the overburden has minor buffering capacity and the mine drainage is typically acidic, potential for dissolution of chemical species in the FGD sludge will be great.

For the Interior case where precipitation is moderately high, leachate generation through the overburden will be significant. The runoff in this region is less because gentle slopes encourage percolation, while the groundwater pumped from the mine will provide dilution. The overburden has significant buffering capacity attributed to the limestone present, resulting in alkaline mine drainage which should discourage dissolution of a number of FGD sludge chemical species.

There is very little precipitation in the Western case, and the amount of leachate generated will be limited. Similarly, there will be little mine drainage collected in the active mining area to provide dilution. As soils in this region are basic and mine drainage is normally neutral to alkaline, dissolution of FGD sludge constituents will not be encouraged. However, the leachate will undoubtedly add to the already high concentrations of dissolved solids naturally prevalent in these waters.

Based on the above discussion, contamination of mine drainage discharge would result from placing sludge in nearly all Eastern, Interior, and Western mines. The acid conditions prevalent in Eastern mines would probably result in the greatest concentrations of FGD sludge constituents contaminating the discharge. Because the major pollutant loadings would be from chloride, sulfate, sulfite, and sodium sludge constituents, treatment (if required to meet effluent guidelines) of the discharge would be costly. None of these chemical species are readily removed by practical wastewater treatment processes, including biological treatment, sedimentation, and precipitation.

As the active mining area advances from the outcrop or lowest depth of overburden, the areas initially receiving FGD sludge are reclaimed and the water table is restored. The sludge, deposited in a loose state, densifies as the overlying static loading from overburden causes consolidation. Permeabilities of the sludge are expected to range from about 10^{-4} to 10^{-5} cm/second, with the lower level attained as the sludge consolidates. The maximum rate of leachate generated from the groundwater underflow passing through the sludge will be a function of the sludge permeability, the hydraulic gradient of the groundwater regime, and the cross-sectional area of the sludge perpendicular to the direction of groundwater flow.

The leachate generated will not be collected as part of mine drainage, but it will exhibit plug flow within the regional groundwater underflow. Leachate flows through the interconnection of voids in both the sludge and the overburden and subsequently through the fractures and discontinuities in the bedrock. Little dilution of the leachate is experienced, although there is slight diffusion at the edge of the leachate plume (or slug).

After mining, relative impacts for each mine case would vary for:

- the amount of leachate produced by the transmission of groundwater underflow; and
- the leachate contaminant level as affected by the background groundwater quality.

For the Eastern case, groundwater underflow is limited by the lack of recharge. However, the water present flows quickly because: (1) the steep surface topography leads to a steep hydraulic gradient, and (2) water often moves through fractured rock faster than through alluvium intergranular openings. Because the background groundwater has little buffering capacity, chemical species prone toward dissolution will contaminate the leachate.

There is moderate underflow of groundwater available for leachate production in the Interior case, but the hydraulic gradient of groundwater underflow is small. As a result, leachate generates slowly and moves slowly from the disposal area. The alkaline background quality of the groundwater underflow encourages precipitation of a number of chemical species, thereby lessening the pollutant potential.

There is very little underflow of groundwater available in most Western mines. Coupled with the small hydraulic gradient of the underflow, leachate production in very limited, and spread of the leachate plume is extremely slow. The basic condition of the soil overburden leads to an alkaline background groundwater which inhibits dissolution of many chemical species in the sludge.

In summary, after mine reclamation a unit of sludge generally produces leachate most quickly in the Eastern surface coal mine and least quickly in the Western surface coal mine. However, the total amount of leachate possible is related to the amount of sludge, and Eastern mines generally have the least capacity for sludge disposal. Western mines have the greatest capacity for sludge disposal, although amounts are limited by the feasibility of long-distance transport. For the estimated average mining scenarios the Eastern mine case annually receives 0.5 million short tons of sludge, the Western mine case receives 1.7 million short tons of sludge, and the Interior mine case receives 2.0 million short tons of sludge.

In general, leachate concentrations will tend to be greatest for the Eastern and Western cases. The Eastern case results in high sludge species dissolution rates because of the nonalkaline background groundwaters most often prevalent. Loadings for the Western case are substantial because of the generally higher concentrations of soluble constituents in FGD sludge produced from Western coals (see Table IV-3).

As mentioned, leachate from sludge will move in a plume (or slug) and dilution will be minimal, although some diffusion of concentrations occurs at the edge of the plume. In addition, concentrations released from the sludge are not expected to noticeably decrease for many years. In accelerated laboratory leaching studies, sludge leachate constituents decreased with increasing pore volumes of water passing through the sludge (until equilibrium solubility constants were reached). Since groundwater moves very slowly, taking tens to hundreds of years for one pore volume of leachate to pass through a layer of sludge, contamination of groundwater in the vicinity of the disposal site could therefore be noticeable for hundreds to thousands of years. However, the impact of the leachate on groundwater will depend importantly on the total quantity of the constituents leached as well as its concentration.

The significance of contaminant levels in the leachate plume will depend on several factors. First, contamination is more significant if it occurs in naturally high quality groundwaters than in highly mineralized groundwaters. Second, the solute transport of most chemical species is lessened by attenuation mechanisms in the aquifer medium. Therefore, the significance of leachate depends on the distance of medium providing attenuation before reaching downgradient wells which provide potable or irrigation water supplies. Significance is also related to the impact of leachate to surface waters according to their prevalence of aquatic organisms and/or use for water supplies.

According to laboratory testing, most of the total dissolved solids in sludge leachate are calcium and sodium chlorides and sulfates, which are not attenuated or precipitated to any measurable degree. A small amount of total dissolved solids is attributed to trace elements such as arsenic, boron, cadmium, chromium, copper, lead, mercury, and zinc. These trace elements are affected by attenuation on clay or organic soils and by precipitation by iron oxides or hydroxides; however, in the assumed surface mine disposal cases, the sludge layer is not mixed with soil matrix to provide attentuation through cation exchange capacity, and iron present in mine drainage may not be in a form which encourages precipitation.

Selenium and chromium are expected to be especially troublesome solubles in the leachate because they dominantly appear in the anionic form in sludge and are therefore not affected by cation exchange and cation oxide precipitation mechanisms. Arsenic and boron are expected to leach because they are not readily precipitated, adsorption being their primary mechanism of attenuation. Aluminum, beryllium, cadmium, copper, cobalt, iron, lead, manganese, mercury, molybdenum, nickel, and zinc are expected to be partially attenuated by precipitation mechanisms under the neutral to alkaline pH conditions prevalent in the Interior and Western surface mine cases. In the Interior case where limestone is present, carbonate salts may form with cadmium, calcium, copper, iron, lead, and zinc. With the acid background groundwater prevalent in the Appalachian plateau contour mines, potential for precipitation of metals is limited.

The quantities of sludge allowable in a particular mine can be estimated for the site-specific geologic and hydrologic features of the mine and surrounding environs, for the composition of sludge placed, and for the relative quality and uses of indigenous groundwaters and surface waters. The maximum leachate produced will depend on the hydraulic gradient of the percolation and/or underflow passing through the sludge layer, the in-situ permeability of the sludge, and the cross-sectional area of sludge perpendicular to the gradients of percolation and/or underflow and can be estimated according to Darcy's law for flow of fluids through porous media. The leachate concentrations leaving the sludge layer will most likely approximate the liquor concentrations of FGD sludge to be disposed. Solute transport modeling, while still in the infant stages of research and development, may be employed to provide some indication of attenuation of the leachate constituents. And finally, the water use criteria and assimilative flow capacity of downgradient surface waters can be used in a steady-state stream model to indicate the amount of leachate discharge allowable.

Biological Considerations

From a biological standpoint, total dissolved solids in general and the high concentrations of heavy metals (especially mercury, cadmium, and zinc) would provide cause for concern if leachate discharges to a small pristine receiving stream. In addition to direct toxicity problems of the estimated increment in mercury, cadmium, and zinc, potential problems of accumulation and synergism would exist, especially in small streams. Mercury and cadmium are persistent, cumulative toxicants, and the toxicity of the latter can be increased by zinc. The high concentrations could provide a source of chronic accumulation and ultimate hazard to man via recreationally valued finfish (e.g., trout) harvested in the receiving stream.

Total oxidizable sulfur (TOS) in leachates may also present a toxicity potential of concern--both in terms of the toxicity of sulfite itself and for the possibility of decreasing dissolved oxygen levels in surface waters (groundwaters for the most part tend to be anaerobic or at least very low in oxygen). Unfortunately, almost no leachate data exist for TOS, and such data would be invaluable in estimating TOS impacts. Based upon the estimated solubility product of calcium sulfite alone in low ionic strength solutions (5 x 10^{-7}), the equilibrium concentration of sulfite would be expected to be on the order of 5-10 ppm. The actual level of sulfite present will depend upon the concentration of calcium and ionic strength of the leachate. Large quantities of calcium sulfate in the sludge will decrease soluble sulfite levels, since calcium sulfate dissolves more readily and increases calcium concentrations. In addition, sulfite may be present in the liquor occluded with the solids; however, it is uncertain how much of this soluble sulfite will persist after handling and disposal of the sludge or how microorganisms in mine water may interact with TOS catalyzed reactions. Therefore, the question of TOS impact cannot be evaluated until further data are available on the presence and persistence of TOS in sludge leachate and in the company of indigenous microorganisms in mine water.

3. Control Techniques to Minimize Adverse Impacts

All control techniques to minimize impacts add to either the cost of disposal or the cost of producing coal. The rationale for control techniques to minimize adverse impacts of technical and environmental significance are discussed within the impact assessment. Possible measures that can be used to mitigate the impacts of the disposal of untreated sludge include: sludge processing or treatment, control of site selection and method of disposal, collection and treatment of sludge leachate or runoff, and restrictions on allowable sludge properties.

Untreated sludge disposed of in surface mines should be filtered or otherwise dewatered to eliminate extra moisture in order to reduce the potential for sludge slide or liquefaction, difficulties in sludge transport and handling, and accelerated leachate production. Sludge treatment by chemical fixation techniques would enhance handling properties and thereby minimize technical impacts, although a well-filtered sludge (possibly admixed with ash) may in many cases be adequate to avoid most adverse technical impacts. A treated sludge should also physically reduce mobilization of pollutants through reduction in the sludge permeability and decreased sludge contact area. The improved physical and handling properties of treated sludges may also provide greater flexibility in sludge placement, which in conjunction with proper site selection may reduce adverse impacts.

Mixing the sludge with clay may provide cation exchange attenuation and with organics may provide adsorption. The soils of the Interior case are characterized by high clay content, organics, and bases. As a result, the soil overburden is an optimum media for mixing with the sludge to provide attenuation. Western soils, on the other hand, tend to be sandy, low in organics, and have little clay. Their attenuation abilities would not be very good, and importation of foreign clay would be economically unfeasible. There is very little soil in the overburden of Eastern contour coal mines; it is doubtful that any mixing of overburden with the sludge would enhance attenuation of solute chemical species.

In the Interior case, where soil overburden may be mixed with sludge, copper and lead would be attenuated readily, while the following species would be to a lesser degree: arsenic, boron, cadmium, fluoride, iron, manganese, mercury, molybdenum, nickel, and zinc. Selenium, chromium, and sulfate would not be attenuated because soil conditions are basic. Calcium and sodium are not likely to participate extensively in exchange due to large concentrations commonly found already adsorbed on clay crystals. Chloride is not attenuated under any circumstances.

In predicting soil attenuation of a particular chemical species, there are several considerations. The quantity and mineral content (e.g., aluminum hydrous oxides) of clay, the pH, the organic matter, and the relative concentrations of other species are all important. One must be aware of the possibility of forming metal chelates with organics, which will act against attenuation. There is also the chance of leaching additional components from a soil in contact with the sludge. Including the mechanism of precipitation, the prediction of attenuation in soil becomes a complicated and individual problem.

Another control technique is simply to limit the disposal of FGD sludges based upon sludge characteristics and site properties. For example, it may be appropriate in certain cases to limit disposal of sludges having high TDS levels and that are not alkaline in nature. The alkalinity is affected by scrubber operation and the type and level of fly ash present. Generally, alkalinity increases with an increase in fly ash (however, most trace elements are concentrated in fly ash). If the sludge layer is kept alkaline, conditions for precipitation of most trace elements are enhanced. For this reason, co-disposal of FGD sludge with coal refuse should be investigated for potential adverse effects on pH and trace element solubility. Since not all coal refuse causes significant acid drainage formation, this issue is site-specific.

Collection and treatment of sludge leachate does not appear to be a viable control technique. Groundwater collection requires expensive pumping wells or infiltration galleries. Also, the principal leachate parameters creating adverse impacts are chlorides and sulfates. Neither of these can be readily treated by existing wastewater treatment processes. Only certain metals are amenable to treatment through oxidation and precipitation techniques.

Operations other than the assumed disposal operation, described as being the least troublesome to mining operations, may improve the impacts. This could include both the method of sludge placement and the form of the sludge deposits created. For example, if part of the rock overburden were deposited in the pit until a depth above groundwater was attained and then part of the soil overburden were deposited above the rock overburden, the sludge layer could then be deposited and covered with remaining overburden. This alteration of the disposal operation would isolate the sludge layer from the groundwater aquifer and provide a clay adsorption media for downward precipitating leachate. However, since the process of digging by shovel or dragline in one pit occurs in a continuous motion by the same machine with overburden replacement in the worked-out pit, this technique would seriously hamper mining productivity.

C. DISPOSAL OF FGD SLUDGE IN UNDERGROUND MINES

1. Range of Conditions Possible

There are two types of underground coal mines showing promise for disposing of FGD sludge. According to the technical ranking order, active underground room and pillar mines and active underground longwall mines show the most promise. Both types of mines are predominantly in the

Eastern and Interior coal regions, with most production from the Eastern region (see Table V-2). Figure V-12 shows a planar view of a conventional room and pillar mine. Figure V-13 shows a cross-sectional view of a longwall mine working face.

Each underground mine is unique in its depth, hydrogeology, and operation. For example, there are some that are essentially dry because of thick, unfaulted shale comprising the floor and roof. There are also many that are wet because of water access through natural cracks, fissures, and joints in the adjoining strata or through induced discontinuities caused by roof caving and mining operations.

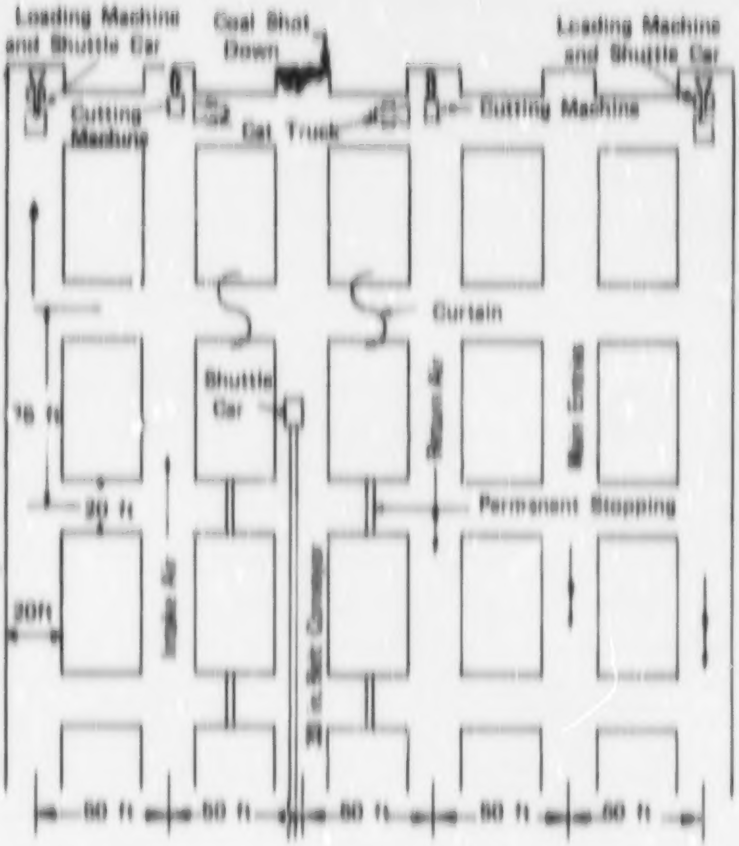
a. Room and Pillar Mines

The production of coal from underground room and pillar coal mines in the Eastern region varies from 0.01 to 4.1 million short tons annually mined from seam thicknesses that vary from 2.5 to 12 feet thick. Overburden depths range from 200 feet to 2,500 feet, with some seams outcropping at a hillside and others buried far below the river valleys. Dips range from horizontal to 10 degrees, with most seams dipping only slightly downward from the outcrop.

An average Appalachian underground room and pillar mine produces about 0.5 million short tons of coal annually. The coal seam mined is about 7 feet thick and located about 400 feet below the ground surface. About 40-50% of the coal is left in place as pillars to support the mine roof from caving. If roof geologic conditions permit and either the mine is deep enough to allow overlying strata to absorb strain deformation or the surface land use can permit subsidence, pillars can be robbed as one retreats back to the access openings. This increases extraction to as high as 80%.

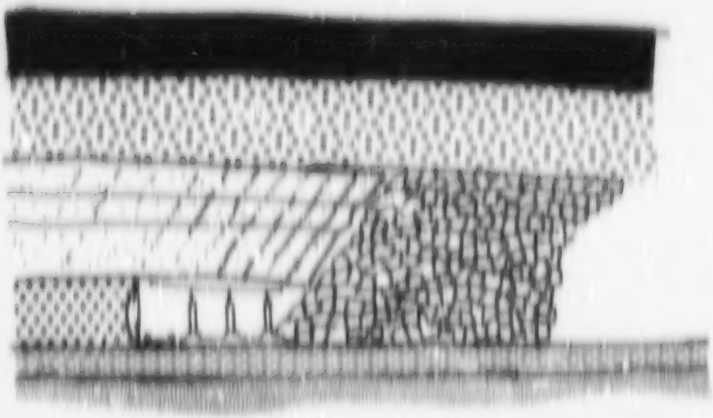
The annual volume of FGD sludge which can be placed in a conventional room and pillar mine is roughly equivalent to the amount of coal removed, considering that sludge cannot be placed in entries. In a room and pillar mine where pillar robbing is practiced, no sludge can be placed in the areas designated for caving.

The coal seams in this region are gently sloping, averaging a 3% slope. Sludge placement could be designed so that sludge decant water and mine drainage is collected upgradient of the disposal area, with sludge settling


Loading Machine and Shuttle Car
Coal Shot Down
Loading Machine and Shuttle Car
Cutting Machine
Cat Truck
Cutting Machine
Curtain
Shuttle Car
Permanent Stopping
20 ft
20ft
Intake Air
Return Air
60 ft
60 ft
60 ft
60 ft
60 ft

Source: Woodruff, S.W., *Methods of Working Coal and Metal Mines*, Vol. 3, Pergamon Press, New York (1966).

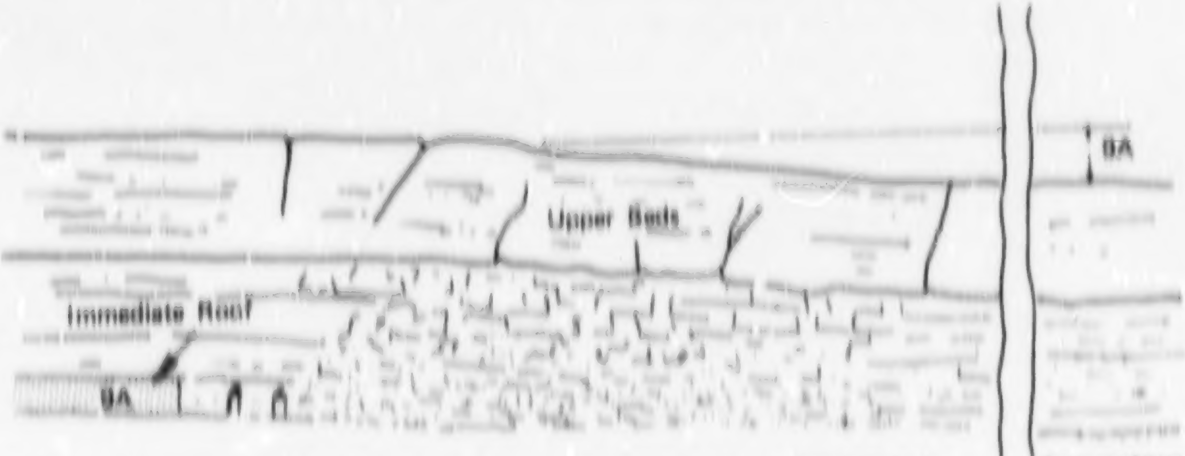
FIGURE V-12 CONVENTIONAL ROOM AND PILLAR COAL MINING MAIN HAULAGE - CONVEYOR



As roof supports are advanced, the roof immediately behind the supports is allowed to cave

Ideal Caving Conditions

Gob swell supports upper beds and yields under their weight, permitting them to slowly bend without breaking



Immediate roof subjected to pressure from upper roof bending action

Immediate roof supported by face supports & bed separation removes loading of upper beds

Immediate roof caves – material fills voids

Compression from upper strata consolidates caved material

Upper beds slowly squeeze the broken immediate roof material to the limit without themselves breaking

Static conditions restored

Source: Weir, J.P., & Kachik, D.J., "Outlook for Long Wall Mining in North America," Mining Congress Journal, 55 (7), 1969.

FIGURE V–13 TYPICAL LONGWALL MINING CROSS SECTIONS SHOWING CAVING ACTION

and filling the downgradient area. The sludge could be placed as a slurry of 20-40% solids, which would be typical of thickener underflow from most of the scrubbing systems. Bureau of Mines experience in backfilling mines with coal refuse reports pumping slurries of 10-50% solids (5). If additional water is needed to maintain an optimum water to solids pumping ratio, mine water drainage can be used.

In the Appalachian coal region of the Eastern region most of the underground coal mining production occurs in West Virginia; second in production is Pennsylvania. The region is humid, with precipitation ranging from about 40 to 60 inches annually and runoff ranging from 12 to 30 inches annually. The coal seams are nearly horizontal and are bordered above and below by other nearly horizontal strata. In the Appalachian plateaus, small to moderate yields of groundwater are derived from the sandstone and limestone aquifers. Most of the high yields in the region come from the river valley alluvium. Some moderate yields are available from the folded and faulted deep rock strata; however, these waters tend to be highly mineralized due to the lack of circulation. Extensive underground mining in this region has complicated the hydrogeology. Groundwater eventually fills abandoned mine voids present below the water table. This groundwater often flows slowly through a series of interconnected mines until finally discharging at a surface outcrop or into the alluvium.

b. Longwall Mines

Most of the longwall mining in the United States occurs within room and pillar mines. Longwall sections are developed when geologic conditions and surface land use allow roof collapse; in deep underground mines underlying hard rock strata, longwall mining may result in no surface deformation. Longwall production in a single mine varies from 0.2 to 1.2 million short tons, with the larger production value occurring in a mine which is almost entirely longwall. The seam thicknesses mined by longwall vary from 2.5 to 12 feet thick, with overburden depths ranging from 200 to 2,500 feet. Most of the seams are horizontal or slightly dipping. However, slopes range up to 10 degrees.

There are about 50 longwall mines operating today. Based on current experience, most U.S. longwall coal mine management believe longwall mining is best suited for 3.5 to 5 foot seam thicknesses overlain by overburden depths of 1,200 feet or more. Average production from longwall mining within a coal mine would be 0.2 million short tons annually.

The amount of FGD sludge which could be placed in a longwall section before controlled roof collapse depends mostly on the speed of the placement operation. Sludge placement must keep pace with mining and roof collapse operations, since the distance allowable between the working face and caved section is kept small to prevent uncontrolled roof collapse. Probably no more than 50% of the volume of coal removed by longwall can be filled by sludge placement prior to roof collapse.

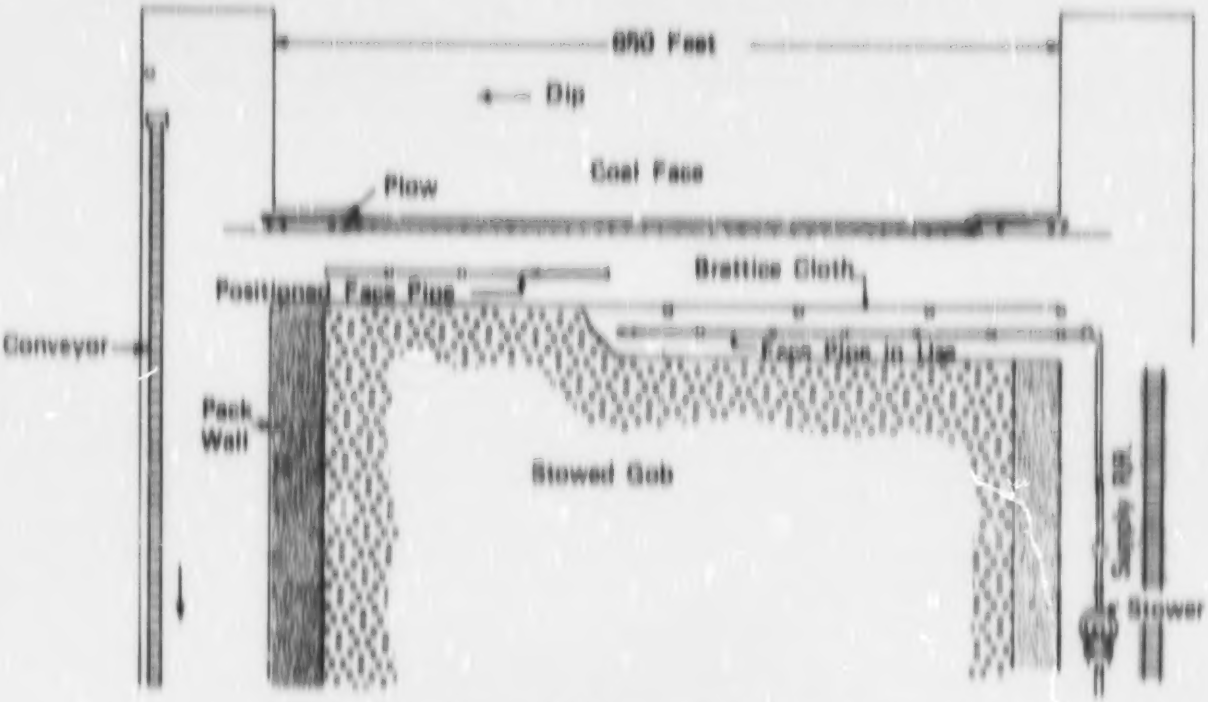
Since the longwall mining case occurs in the same region as the room and pillar case, hydrogeology described above applies. Groundwater seepage from overlying strata may be more severe in longwall cases because roof collapse induces cracks, fissures, and joints in the overlying strata which allow groundwater infiltration to the mine area. However, strata below the coal seams remains undisturbed and maintains its natural permeability for water leaving the mine.

2. Impact Assessment

Disposal in the mined-out portions of an active room and pillar mine where pillars have not been robbed would involve hydraulic backfill using a pumped slurry technique. The sludge could be either thickener underflow from the scrubbing system or a slurry of treated sludge which would set up in the mine. While placement of treated sludge blocks is possible, as is construction of support pillars with treated, concrete-like sludge, these procedures are not considered technically and economically promising.

In order to contain the sludge, bulkheads between pillars would be constructed and sludge then introduced through boreholes from the surface. The concept is sketched in Figure V-14, which gives a plan and cross-section view. Pneumatic placement of sludge is also technically feasible. However, because of the additional sludge processing required to obtain the low sludge water content necessary for pneumatic stowing, hydraulic placement appears more promising.

In a longwall mining operation, hydraulic placement would not be acceptable because of potential hazard to miners as the roof caves upon


650 Feet
Dip
Coal Face
Plow
Brattice Cloth
Positioned Face Pipe
Conveyor
Face Pipe in Use
Pack Wall
Stowed Gob
Supply Pipe
Stower

Conventional Pneumatic Stowing Layout
for a Longwall Face

Source: Courtney, W.J., and Singh, Madan M., "Pneumatic Stowing: It Must be Looked At Now," *Coal Mining and Processing,* 11 (2), 1974.

FIGURE V–14 LONGWALL STOWING – CONVENTIONAL

a slurried material. Therefore, disposal in the working face of an active longwall mine involves pneumatic stowing of relatively dry sludge, as indicated in Figure V-15. The dry sludge could be either a filtered, untreated sludge or a soil-like, chemically treated sludge. A water spray would be used to keep the dust under control.

a. Technical/Physical Impacts

The first reported backfilling of mine workings was for hydraulic placement of crushed coal mine waste underground at Shenandoah, Pennsylvania in 1864 (6). Since then, hydraulic backfilling has been mostly applied in Europe and India. Many European coal mines underlie highly developed industrial areas or commercial waterways requiring protection from subsidence. The backfilling contributes to roof control and permits a greater percentage of coal recovery from the mine. Recently, hydraulic backfilling in Germany and Great Britain has been replaced by pneumatic backfilling.

Coal mine refuse has been placed in the abandoned mines of eastern Pennsylvania. The old coal washing waste bank material was crushed and pumped down holes into abandoned and flooded anthracite mines. Also, dry fly ash has been blown down holes into an abandoned Pennsylvania mine. Although the above backfilling projects have been accomplished, there is little information which resulted from placement of a fine grained material in mines. It would appear that filling the voids of these abandoned mines has sealed pyrite from oxidation to acid drainage, lessened subsidence attributed to pillar deterioration, displaced stagnant underground mine pools, and decreased connecting underground channels for groundwater flow and methane gas.

Subsidence Control

The following discussion explains the cause of subsidence, the need for subsidence lessening, and the properties of FGD sludge that might help to lessen subsidence. Removing underground minerals through mining can result in the roof of the mine collapsing and the overburden falling into the mine void, subsequently causing a subsidence trough at the earth surface. Factors affecting the degree of subsidence are the height, length, and width of the mine void; the depth and character of the overburden; the size, character, and distribution of pillar supports; backfill

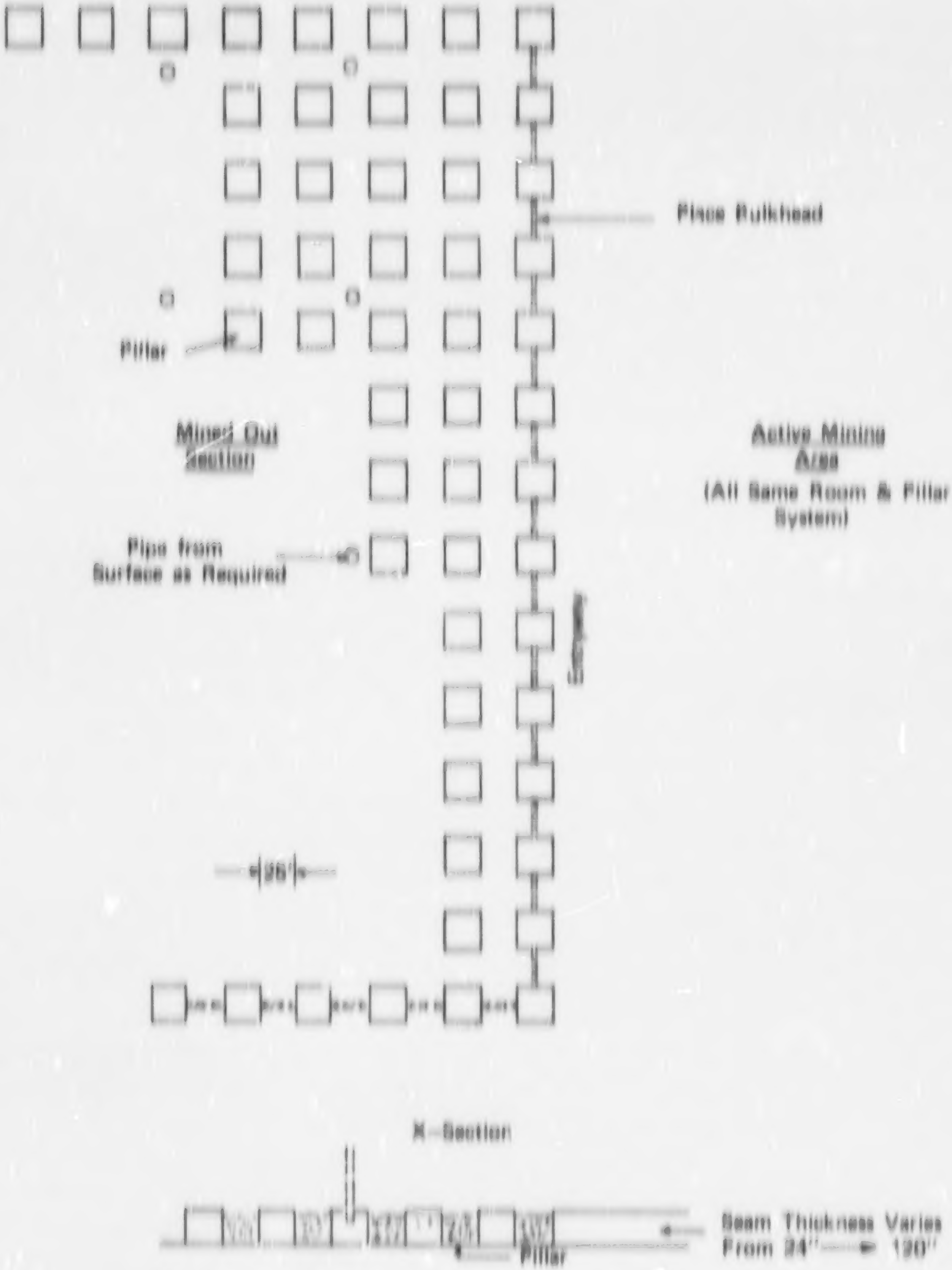

Pipe Bulkhead
Pillar
Mined Out Section
Active Mining Area
(All Same Room & Pillar System)
Pipe from Surface as Required
25'
X-Section
Seam Thickness Varies From 24" → 120"
Pillar

FIGURE V-16 PLAN – ROOM AND PILLAR MINE

amounts and character; movements of underlying strata; and groundwater movement. Generally, the differential ground movements (strain, slope, and curvature) of the surface decrease with increasing depth of mining, and a critical depth based on allowable strain of surface structures can be estimated (10).

Near-term subsidence occurs over active longwall or pillar robbing sections after a critical volume has been extracted. Observations taken at numerous British underground coal mines show that 94% of final subsidence occurs immediately after complete critical extraction (11 and 12). Near-term subsidence does not occur during active room and pillar mining by conventional means (where pillars are left in place). However, long-term subsidence may occur over conventional room and pillar mines where the pillars have deteriorated by groundwater dissolution of the solubles.

The maximum depth of subsidence possible is about 90% of the seam thickness. The total U.S. land area undermined for production of coals, metals, and nonmetals has been estimated as about 7-1/2 million acres (5). Nearly one-third of this acreage exhibits some subsidence. Of this subsidence, 85-95% was believed related to coal mining, 3-10% was attributed to hard rock mining, and 2-5% was attributed to nonmetal mining. About 2 million acres have been reportedly affected by coal mine subsidence (9). Less than 5% of the 2 million acres show significant subsidence affecting existing land use (7 and 8).

Backfilling FGD sludge into underground mines has limited potential to lessen short-term subsidence (i.e., pneumatic stowing into a longwall section before roof collapse) and to lessen long-term subsidence (i.e., hydraulic stowing into a mined-out room and pillar section where pillar robbing is not permitted). Placing sludge in the void left from extraction may lessen the depth of the subsidence trough. While the backfill material would not have the bearing capacity of the original ore seam, it would provide some support upon consolidation. Hydraulic stowing with coal refuse in British and French coal fields has lessened the maximum subsidence factor of 90% to ranges of 25-45%. Pneumatic stowing has lessened factors to ranges of 45-55%.

The ability of FGD sludge to lessen subsidence depends upon the compression index of the placed sludge. The compression index, obtained from soil mechanics consolidation tests, measures the amount of settlement the sludge will experience under varying loadings (i.e., the weight of the overburden). Each sludge will have different compression indices for a range of loadings, and each mine will vary in the loadings applied. Therefore, the subsidence lessening potential of sludge can only be estimated on a site-specific basis. However, since longwall mining and pillar robbing are currently allowed only under rural areas, without buildings or roads susceptible to damage caused by earth settlement, the importance of reducing short-term subsidence is minor.

The positive benefits to subsidence control accrued from FGD sludge backfilling are related to long-term subsidence in room and pillar mines. In these mines, sludge placement would limit the long-term deterioration of support pillars by partially sealing them from air exposure and groundwater dissolution. The sludge would also apply some lateral pressure to support the pillars.

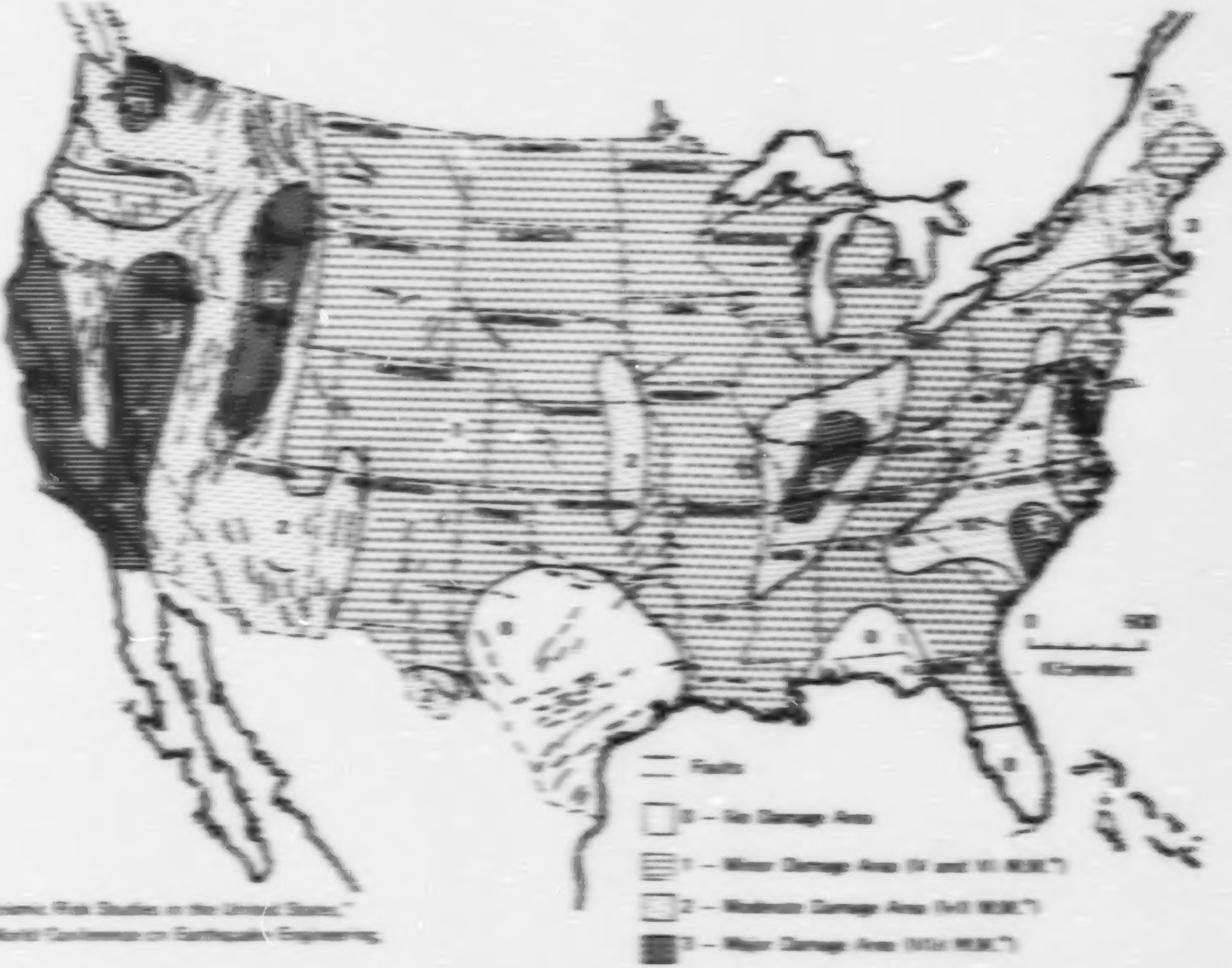
Liquefaction of FGD Sludge

Certain FGD sludges have the potential to liquefy under certain conditions. Even so, the following discussion explains why sound engineering prevents any hazard from this sludge property. Liquefaction is a deformation due to buildup of high pore water pressures created by either cyclic or static stress applications. Earthquakes result in dynamic shear stresses and shear strains which cause dislocation of grain-to-grain contact. This causes volumetric compaction in dry materials; however, saturated materials retard compaction until the pore water can drain. Pore water pressures increase as the intergranular stresses decrease. If the intergranular stresses are eliminated, the material has no shear resistance and flows like a liquid (14).

FGD sludge which has been hydraulically placed in a conventional room and pillar mine has the potential to liquefy for the following reasons.

- Hydraulically placed sludge will have a low relative density, lower than coarser hydraulic fills typically employed. Typical sandfills in mines have a relative density averaging 55% (6). Hydraulic fills for foundation support having less than 10% fines typically achieve densities of 50-60% without compaction (13). Liquefaction potential of a material increases with decreasing relative density (14).
- FGD sludge is uniformly graded with most particles in the silt size, and liquefaction occurs most easily in uniformly graded soils of the fine sand and silt sizes (14).
- Most sludges appear to be relatively cohesionless, although there has been little testing of engineering properties to confirm this. Despite the variance of particle shape from needles to platelets, the surface appears unreactive and intergranular attractive forces appear limited. Tests for Atterberg limits indicate some sludges have little or no plasticity.
- Sludges hydraulically placed in underground mines would most likely remain saturated. FGD sludge does not drain readily, and the flow of water from the disposal area would be restricted by the permeability and discontinuities of confining strata. Continuous recharge from overlying groundwaters is expected.
- Sludges have a low specific gravity which limits their ability to maintain intergranular contact under cyclic loading. Sludges have specific gravities from 2.3 to 2.6, while soils typically range from 2.6 to 2.8.

While surmising that sludge is susceptible to liquefaction, the impact is probably not significant. The significance of liquefaction potential is directly related to the seismicity of a site and the confining strengths of the surrounding materials or structures. Most underground coal mining occurs in seismically inactive areas of minor risk (compare Figure V-1 and Figure V-16). The sludge would be confined by the unmined strata, the pillars left in place, and the bulkheads between pillars. The bulkheads can be readily designed to withstand both cyclic earthquake loading and the sudden loading from liquefied sludge.


0
1
2
3
0 500
Kilometers
Faults
0 — No Damage Area
1 — Minor Damage Area (V and VI MM*)
2 — Moderate Damage Area (VII MM*)
3 — Major Damage Area (VIII+ MM*)

*Modified Mercalli Intensity Scale (1956).

Source: Algermissen, S.T., "Seismic Risk Studies in the United States," presented to the 4th World Conference on Earthquake Engineering, Chile, 1969.

FIGURE V–15 SEISMIC RISK AREAS AND FAULT ZONES IN THE UNITED STATES

Corrosion Potential

There is some potential that the long-term exposure of the bulkhead to FGD sludge may somewhat weaken its strength. Sulfates are corrosive to concrete under acidic conditions. The stronger the concentration of the sulfate salts, the more active the corrosion. The sulfates react chemically with the hydrated lime and hydrated calcium aluminate to form calcium sulfate and calcium sulfoaluminate, respectively. These reactions are accompanied by considerable expansion and disruption of the concrete. The relative degrees of attack on concrete by sulfates are given below.

ATTACK ON CONCRETE BY SOILS AND WATERS CONTAINING VARIOUS SULFATE CONCENTRATIONS

Relative Degree Sulfate Attack	Water-Soluble Sulfate (as SO_4) in Soil Samples	ppm Sulfate (as SO_4) in Water Samples
Negligible	0.00 to 0.010	0 to 150
Positive[a]	0.10 to 0.20	150 to 1,000
Considerable[b]	0.20 to 0.50	1,000 to 2,000
Severe[b]	Over 0.50	Over 2,000

[a] Use type II cement.

[b] Use type V cement.

Source: "Concrete Manual," A Water Resources Technical Publication, United States Department of the Interior, Bureau of Reclamation, 7th edition.

Sulfate in sludge is often in the range of 2,000 to 4,000 ppm. From the above table, sludge falls into the third category, where the degree of sulfur attack is severe. In this case, the concrete which should be used for bulkhead construction is portland cement, type V. This concrete has low tricalcium aluminate content and therefore is the least susceptible to sulfate corrosive action. The Ferrari grade of portland cement, with virtually no tricalcium aluminate content, was found to have the optimum sulfate resistance, with concretes resisting 15,500 ppm sulfate for over 25 years without any sign of corrosion (15); however, the Ferrari grade is not readily available in the United States.

Sulfite content in sludge may be as serious a corrosive as sulfate. However, there is no information to indicate the level of corrosion which might be expected for given sulfite concentrations. In addition, there is no information for determining the synergistic effect on corrosion that the combination of chemical species in FGD sludge might create. Corrosion testing should be done using concrete with type V cement. Because this concrete takes three months, instead of one month, to cure, lead time for adequate sample preparation is significant. In addition, use of the type V cement for bulkhead construction requires early construction to ensure complete curing before sludge placement.

In general, massive structures are more resistant than thin structures, and stagnant conditions result in less corrosion than flowing conditions. Corrosion resistance is affected by the porosity of the concrete as well as by chemical factors. Where chlorides are present, they may or may not attack the concrete. However, if they penetrate a porous concrete, they can cause corrosion of the reinforcing steel and spalling. Lowering the water-cement ratio when building the bulkhead will help lower the permeability to chlorides and help protect embedded steel. Also, coating the steel with epoxy will help mitigate corrosion.

Effects on Productivity

Conventional underground room and pillar coal mining results in 50-60% ore extraction. The remainder is left in place as pillars. Longwall mining allows for about 80% ore extraction. Stowing of FGD sludge would impact upon the potential recovery of coal resources from a conventional room and pillar mine, but no impact upon future recovery would occur in the longwall mine.

Pneumatic stowing of sludge into a caving face of a longwall mine is not a simple job. There are potential safety hazards to operators located in the vicinity of the caving. In addition, noise from the pneumatic systems and dust from the blowing of dry FGD sludge fines into the caving face would impact upon working conditions of the longwall operation.

FGD sludge disposal underground would impact upon room and pillar mine productivity because of the increased labor and equipment involved. Increased handling involves creating adequate drainage for sludge leachate and decant collection and pump-out. The sludge would be slurry backfilled at a higher water to solids ratio than desired for the final settled sludge mass. Of necessity, there would be an excess of water requiring removal and potential treatment before discharge. Drainage would have to be appropriately designed so that water would not seep into the active portions of the mine. Borehole drilling, bulkhead construction, piping, pump-out water storage, and pump-out water treatment employed as part of the disposal operations will increase the handling requirements and use of the surface land above the mine. Congestion on the surface may result and hinder the movement of coal from the mine.

In the case of longwall mining productivity as affected by FGD sludge disposal, the impacts are expected to be less. The sludge would have to be dry and therefore would require no special drainage or mine water pump-out treatment. Also, no bulkhead construction would be required. In Germany, stowing machines which allow lateral discharge by pneumatic backfill equipment are currently in use. Continuous miners often have to slow down to allow the backfilling to keep up, thus maintaining a short distance between the cutting wall and the caving. Stowing takes place during the same shift as ore excavation, and productivity loss is experienced.

Potential Beneficial Effects (AMD Control)

Sludge placement in underground room and pillar mines may allow improved ventilation control because of the filling of the mine void. Similarly, filling the mined-out portion of the mine may prevent some migration of methane into the mine. Explosion and fire hazard would be reduced. Another potential benefit to the mine atmosphere may be attributed to the usually alkaline nature of FGD sludge.

FGD sludge may, upon disposal in underground coal mines, partially neutralize existing acid mine drainage. Acid drainage is probably the most familiar and widespread water quality problem associated with certain coal seams mined. The oxidation of reactive forms of iron pyrite (FeS_2) in the presence of moisture leads to acidity, according to the following reactions:

$$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4 \qquad \text{(Eq. 1)}$$

$$4FeSO_4 + O_2 + 10H_2O \rightarrow 4Fe(OH)_3 + H_2SO_4 \qquad \text{(Eq. 2)}$$

The neutralization of acid mine drainage involves oxidizing ferrous iron to ferric iron and raising pH by addition of an alkaline. Table V-9 shows the potential for limestone treatment of acid mine drainage having different ferrous concentrations.

There are many alkaline reagents being used to neutralize acid drainage. The five most common compounds are (17):

Reagent	Chemical Formula	Relative Efficiency	Relative Cost
Limestone	$CaCO_3$	.8	1
Quick Lime	CaO	.9	4.5
Hydrated Lime	$Ca(OH)_2$	.95	5
Caustic Soda	$NaOH$	.99	18
Soda Ash	Na_2CO_3	.99	16

Limestone is the lowest cost neutralization reagent. The relative efficiency for lime $Ca(OH)_2$ and caustic soda ($NaOH$) is high but relative cost is high as well. Overtreatment of acidic water with $NaOH$ or $Ca(OH)_2$ can make it too alkaline. On the other hand, it is impossible to overtreat water with limestone. In this case, pH of 8 is seldom exceeded (16).

Since FGD sludge contains some of the above reagents, there is a possibility it can be used instead. Its neutralizing capacity is due to calcium carbonate ($CaCO_3$) and hydroxyl (OH^-). Typical compositions of different sludges are as follows:

	Moles of $CaCO_3$/liter	pH	Moles of OH^-/liter
Limestone Sludge	1.75	7	10^{-7}
Lime Sludge	0.30	11	10^{-3}
Dual Alkali (caustic soda)	0.30	11	10^{-3}

Since the limestone sludge usually contains significant concentrations of unreacted calcium carbonate, it is probably the best FGD sludge for neutralization purposes. The hydroxide levels shown for each of the sludges are low and not expected to provide much neutralization.

TABLE V-[illegible]

MINE DRAINAGE CLASSES

Chemical Parameter	Class I Very Acid Not Oxidized Not Neutralized	Class II Slightly Acid Partially Oxidized and/or Neutral	Class III Neutral to Alkal. Totally Oxidized and Neutralized	Class IV Neutral to Alkal. Not Oxidized Not Neutralized
pH	2 - 4.5	3.5 - 6.6	6.5 - 8.5	6.5 - 8.5
Acidity[a]	1,000 - 15,000	0 - 1,000	0	-
Ferrous Iron (mg/l)	500 - 10,000	0 - 500	0	50 - 1,000
Ferric Iron (mg/l)	0	0 - 1,000	0	0
Aluminum (mg/l)	0 - 2,000	0 - 20	0	0
Sulfate (mg/l)	1,000 - 20,000	500 - 10,000	500 - 10,000	500 - 10,000

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[a] Expressed as approximate number of milligrams of $CaCO_3$ required to neutralize a liter of mine drainage of each class.

Source: Reference (17).

In a room and pillar mine with very acidic drainage (1,000-15,000 expressed as milligrams of $CaCO_3$ required for neutralization), up to 143 grams of a settled limestone sludge (50% solids having 30% $CaCO_3$) would be needed to neutralize 1 liter of acid drainage. The degree of neutralization achievable in a specific mine will depend on the acidity of the drainage and the ratio of sludge to drainage available in the disposal operation.

Acid mine drainage in underground mines also contains unoxidized sulfide which can be released into the atmosphere as follows:

$$S^{=} + 2H^{+} \rightarrow H_2S\uparrow \qquad \text{(Eq. 3)}$$

The alkaline substances in the sludge would raise the pH of the mine drainage and convert H_2S to HS^-, thereby decreasing the amount of hydrogen sulfide evolved as a gas. Since FGD sludges contain no sulfide, addition of nonalkaline sludge to the mine would not be expected to increase the evolution of hydrogen sulfide.

Calcium sulfite in many FGD sludges will react with sulfuric acid in acid mine drainage of pH less than 4. The reaction product is sulfur dioxide, as shown in the following equation:

$$CaSO_3(S) + H_2SO_4 \xrightarrow[pH\ <4]{} CaSO_4 + H_2O + SO_2\uparrow \qquad \text{(Eq. 4)}$$

The above reaction may occur in mines having the worst type of acid mine drainage (pH 2.5-4). SO_2 evolution should occur only in the initial period of disposal because the buffering capacity of the sludge would eventually raise the pH of mine drainage.

For totally oxidized sludge (all $CaSO_4$) no reaction occurs. Only at pH levels less than about 2.5 would there by any appreciable dissolution of calcium sulfate to form soluble bisulfate:

$$CaSO_4(S) + H_2SO_4 \xrightarrow[pH\ <2.5]{} Ca(HSO_4)_2 \qquad \text{(Eq. 5)}$$

Simple filling of the mine void and sealing exposed pyrite will be the principal deterrent to future acid drainage formation in active underground mines. Filling the mine void curtails exposure of coal and its pyrite constituent to air oxidation, thereby limiting formation of sulfuric acid. Groundwater has very low dissolved oxygen, and sulfite content of certain sludge would consume this small amount, leaving little or no oxygen for even slow acid drainage formation.

b. Environmental Impacts

Sludge Leachate

All underground coal mines have some infiltrating water. Water enters the mine from rock strata above, below, and adjacent to the mine void. The amount of water depends on several factors. One factor, shown on Figure V-16, involves the location of the mine either above or below the groundwater table. Since the regional water table varies with the seasons as precipitation, evapotranspiration, and percolation fluctuate, a mine may be within the groundwater reservoir for only a portion of the year. Essentially, any water present above the mine will eventually infiltrate into the mine. Waters entering from below are dominated by artesian pressures and will rise into the mine relative to their hydrostatic head. Although mines within the groundwater reservoir have the greatest potential for receiving infiltrating waters that can generate leachate (especially as the depth of the mine increases and the hydrostatic head of water respectively increases), even mines above the water table receive percolation as it passes through to replenish the underlying groundwater reservoir.

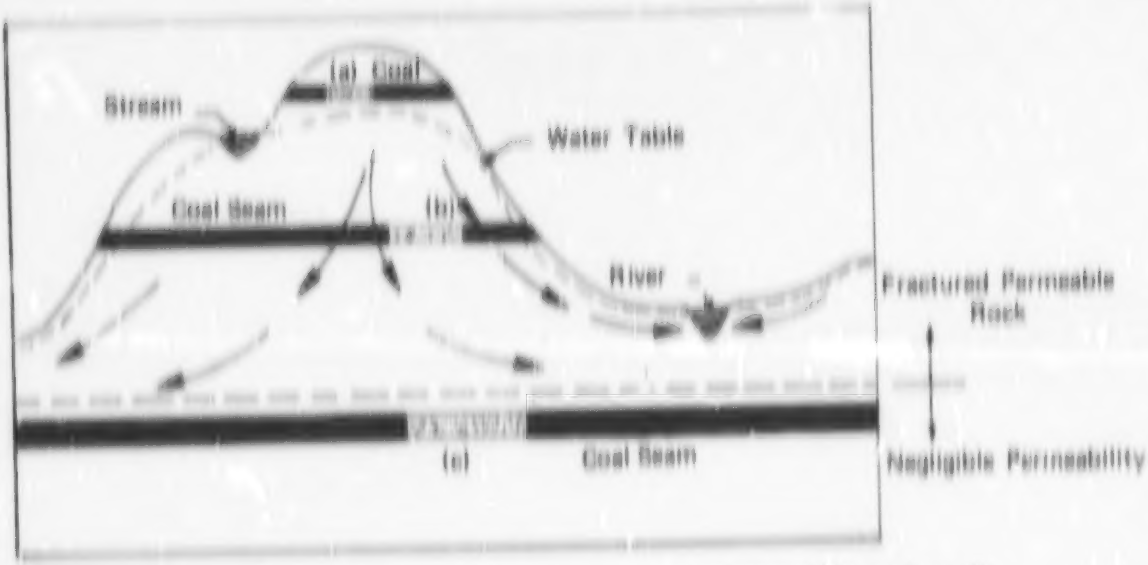
Underground water travelling through rock moves through faults, joints, fractures, and solution cavities which occur naturally, and through boreholes collapsed roof and mined-out sections created by mining. Some interaggregate flow through rock pores may also participate in the groundwater movement, especially in porous limestone or sandstone strata which serve as aquifers. The overall movement of the regional groundwater flow relates to the surface topography and is essentially laminar. However, locally the groundwater follows the paths of the multiple discontinuities. As a result, the leachate does not move in a plume as in unconsolidated sediment but in series of channelized slugs. Regionally, the rate of flow is controlled by overall strata permeability, even though locally, groundwater flows more quickly through individual fractures than through porous medium. There is some possibility that the fine grained sludge particles would fill the fractures of strata underlying the sludge, thereby decreasing its ability to transmit leachate.

Because the hydraulic gradient of regional groundwater flow is dependent on the surface topography, coal seams located in hills are subject to a steep hydraulic gradient. Deeper seams are affected by the changing gradient as groundwater recharges river valley alluvium. Very deep seams may experience little or no flow, as strata are essentially impermeable (see Figure V-17).

During mining, groundwater is removed from the active area. If the coal seam is bound by aquicludes or relatively unfaulted strata which do not transmit much groundwater flow, only small amounts of groundwater must be pumped from the mine as it slowly infiltrates and collects in a sump. If the coal seam is bound by one or more aquifers, it may be necessary to pump a lot of water and depress the water table. In either situation, sludge placed in a mined-out section near the active working area would probably receive little groundwater infiltration.

Sludge placed hydraulically in a mined-out section of an active room and pillar mine will probably be obtained from the thickener underflow of the scrubber. No addition of water to the thickener underflow would be needed to allow slurry pumping. During disposal the suspended sludge particles would settle, and the sludge decant water would be continuously removed to make room for more sludge. This decant water essentially would have the concentration of sludge liquor, so collection and treatment of the decant water would be a necessary part of the disposal operation and a troublesome one. The most concentrated species in the sludge liquor are dissolved solids of chloride, sulfate, sulfite, and sodium (see Table IV-5) which are not readily removed by ordinary wastewater treatment processing. Biological, sedimentation, and precipitation processes do not remove these constituents, and the more sophisticated processes which do remove them are very costly.

As mining proceeds away from the sludge disposal area or as the mining is completed and the mine sealed, the area becomes removed from the influence of pumping. Groundwater will infiltrate the sludge disposal area until the voids are filled and then will develop a steady-state movement into and out of the area. If the adjoining strata are relatively undisturbed by mining, which is the case in active conventional room and pillar mines, the groundwater flow will resume its original flow patterns. If, however, the adjoining strata is disturbed, the groundwater flow into the mine will be substantially altered. In a longwall mining area, overburden fracture induced by roof collapse allows substantial infiltration of overlying


(a) Coal
Stream
Water Table
Coal Seam
(b)
River
Fractured Permeable Rock
(c)
Coal Seam
Negligible Permeability

(a) Underground mine containing sludge lies above groundwater table, and results in no significant leachate generation

(b) Underground mine containing sludge lies below groundwater table; leachate is produced and moves with regional groundwater flow toward discharge in a surface water.

(c) Underground mine containing sludge lies well below (over 500') major river valley, therefore leachate is confined by limited groundwater movement within dense strata.

FIGURE V–17 REGIONAL GROUNDWATER MOVEMENT IN SEALED UNDERGROUND MINES

waters into the mine. Also, deterioration of pillars in abandoned underground mines has led to long-term subsidence and extensive infiltration of overlying waters. In Appalachian plateaus where extensive mining has occurred, interconnection of abandoned underground mining coupled with augered holes that connect underground mines to surface contour mines encourage substantial underground channeling and also discharge of groundwater to the surface and into the alluvium.

As noted, leachate generated from sludge disposal is a direct function of infiltration waters. The amount of water infiltrating varies for local conditions of strata and sludge in the disposal area. This variation is very site-specific and cannot be covered in detail in this report. Placed sludge for the room and pillar mine will probably be slightly more permeable than in the longwall mine after caving. On the other hand, room and pillar mining results in little disturbance to adjoining strata and therefore does not result in an increased flow of groundwater into the mine; longwall mining results in substantial fracturing of adjoining strata and subsequent increasing of infiltration.

In addition to the amount of water infiltrating the sludge disposal according to the type of mining, infiltration varies for regional conditions of water balance, depth of seams mined, and surface topography. Most of the underground mining occurs in the Eastern coal province and principally within the Appalachian plateaus of West Virginia, Pennsylvania, and eastern Kentucky. Underground mining also occurs to a lesser degree in the Interior coal region within Illinois and western Kentucky. The principal difference between these coal regions is the hydraulic gradient of groundwaters within the mining area. For Eastern mines located in the plateaus the hydraulic gradient is steep. And for Eastern mines located below the river valleys the hydraulic gradient is small. In conclusion, the greatest potential for leachate generation occurs in the Eastern plateaus due to the steep hydraulic gradient.

The leachate concentrations emanating from FGD sludge are related to the initial chemical composition of the sludge and the background quality of infiltrating groundwater. Fewer chemical species will leach under alkaline conditions, especially metals which form precipitates. Some species are not affected, though, by the differences in alkalinity of infiltration water. Chloride, sulfate, sulfite, and sodium are not expected to be appreciably attenuated under any pH condition, and resulting leachate concentrations will directly relate to the initial chemistry of the sludge. Outside of precipitation, the attenuation mechanisms which occur in soil (such as ion exchange and adsorption) do not appreciably occur in rock.

In general, the groundwaters in the Eastern plateau mines have less buffering capacity than the groundwaters in the Interior mines. The buffering capacity of the groundwater is principally related to the existence of limestone in strata above the coal seam. Also, the buffering capacity is related to the generation of acid mine drainage in mined seams above the one being considered for sludge disposal. As a result of alkalinity differences between the regions, Eastern mines may result in more concentrated leachate from sludge than Interior mines.

Placing FGD sludge in underground mines within the groundwater regime could result in significant groundwater contamination which could continue for hundreds to thousands of years. Therefore, the site-specific nature of proposed mine disposal alternatives must be carefully investigated. The following discussion explains the issues most significant to assessing groundwater contamination potential.

The amount of leachate produced from FGD sludge disposed in an underground cavity depends on the passage of waters through the sludge. The limiting factor in leachate generation may be either the amount of water the sludge will transmit or the amount of influent waters infiltrating the mine and its driving force (hydraulic gradient as a function of hydrostatic head).

In situ permeability of the sludge varies for the type of sludge, the method of placement, and the chemical treatment of the sludge, if any. Untreated sludge hydraulically placed in an underground room and pillar mine will initially be in a slurry with about 20-30% solids, then will deposit into a layer or series of cone shapes having decreasing permeability with time. Settled sludges tested in a laboratory averaged 10^{-5} cm/second permeability. Untreated sludge pneumatically stowed in a longwall section will be placed in a loose dry state, but the caved roof will consolidate the sludge with time under its static loading. There is no data simulating sludge permeability under these conditions.

In addition to the above aspects of FGD sludge permeability, there is some possibility that some sludges of high alkalinity may self-seal, with precipitates from the infiltrating waters filling void spaces between the sludge particles. If the sludge were to self-seal, even if only on its exposed surface, waters would channel around the sludge deposit.

Biological Considerations

Groundwater which has flowed through the sludge and become contaminated can reach surface water by two pathways: (1) mine sump pump-out may be discharged to a receiving stream after some treatment to effluent guidelines limitations, and (2) mine water flow within the groundwater reservoir to its discharge into a spring or river valley alluvium.

Once leachate reaches a surface water, the significance of impact depends on the assimilative flow capacity of the receiving water, its current and indigenous water quality, and its existing and desired uses. Total oxidizable sulfur (i.e., sulfite) present in the sludge leachate will pass through the anaerobic groundwater environment without being appreciably oxidized and will exert an oxygen demand on the receiving water. Depletion of dissolved oxygen, if substantial, will adversely affect aquatic organisms. Also, some of the trace metals, if not significantly attenuated in the groundwater regime, can bioaccumulate through the food chain and ultimately affect human health.

3. Control Techniques to Minimize Adverse Impacts

Control techniques are discussed within the impact assessment. A summary of techniques for underground coal mines is presented below.

In underground room and pillar coal mines, FGD sludge placement raises technical issues of minimal subsidence control and potential spontaneous liquefaction. These issues would be limited if FGD sludge were treated prior to disposal. The treatment method preferred would result in a concrete-like sludge matrix, taking only a short time to set up underwater. Care would have to be taken so that treated sludges do not "set up" in pipes or boreholes.

In the underground room and pillar case, highly acid drainage coupled with sludge disposal results in possible concrete and steel corrosion (used in bulkheads) and a potential for sulfur dioxide gas formation. These impacts may be minimized by restricting sludge disposal to nonacidic mine water environments.

Impacts of leachate on groundwater are not readily mitigated. Sludge drainage and decant water collected during disposal operations may be processed for pollutant removal of some heavy metals. However, leachate over the long term can be lessened by two procedures. First, the mine selected for disposal can be located above the groundwater table. Second, sludge chemical treatment can be employed to decrease the exposed surface area of the sludge and decrease sludge permeability, thereby decreasing leachate production. While some treatment processes involve setting up underwater, there is very little data regarding the physical/chemical stability of treated sludge under long-term saturated conditions.

The impacts of the longwall mining case do not require mitigation by sludge treatment. The disposed sludge is dry and consolidated by caved overburden. The amount of longwall mining is limited and the resulting sludge and subsequent leachate is limited.

D. DISPOSAL OF SLUDGE IN SELECTED UNDERGROUND MINERAL MINES

1. Lead-Zinc Mines

a. Range of Conditions Possible

FGD sludge disposal in abandoned or mined-out portions of active room and pillar lead-zinc mines appears promising. These primarily occur in Southeast Missouri, which we refer to as the interior region.

Lead-zinc ores occur within a limestone matrix, which accounts for the alkaline conditions of the mine drainage. The mines are generally deep, with overburden depths ranging from 1,000 to 1,600 feet. The ore body thickness ranges from 10 to 100 feet. The ore body is horizontal, with slight dips and undulations up to about 2 degrees. Production of an active room and pillar lead-zinc mine varies from 0.4 to 2.5 million short tons annually, with most mines being at the lower production level (see Table V-4).

There are about seven active mines operating in the Southeast Missouri lead-zinc ore region. An average ore body thickness of 30 feet is mined, with panel widths of about 40 feet. As much as 80% of the ore is extracted if the pillars are "slabbed" (robbed). Because of the very large average panel openings, bulkhead construction along a line of pillars would be costly to implement.

No bulkhead construction would be necessary in abandoned lead-zinc mines, and blind flushing from boreholes drilled from the surface could be accomplished (as shown in Figure V-18). From some fifteen abandoned lead-zinc mines in the Southeast Missouri region about 400 million short tons of ore have been removed. The voids created are still believed to be largely intact, although filled with groundwater, and the space for sludge disposal is substantial.

Sludge would be pumped as a slurry, with solids content similar to that coming from a thickener underflow (about 20-40% solids by weight).

b. Impact Assessment

In both the active and abandoned lead-zinc mines the sludge would be hydraulically placed as a pumped slurry. In the active mines, sludge would be hydraulically placed by controlled flushing from within the mine or by blind flushing from boreholes. In the abandoned mines, sludge would be hydraulically placed by blind flushing from boreholes drilled from the surface. Mine water and decant water must be continuously pumped from the abandoned mines as sludge settles.

All of the lead-zinc mines experience wet conditions. The abandoned mines are typically filled with water, while the active mines are continuously pumped to permit mining. The water is alkaline because the rock environment is largely dolomitic; pH is generally about 8. While the lead-zinc occurs within a limestone matrix which serves as a high yield aquifer, artesian groundwater supplies in the region are generally derived from the water-bearing sandstones above and separate from the lead-zinc ore seam.

Technical Impacts

We will not attempt to duplicate in this section the background material on subsidence, sulfur dioxide gas formation, concrete corrosion,

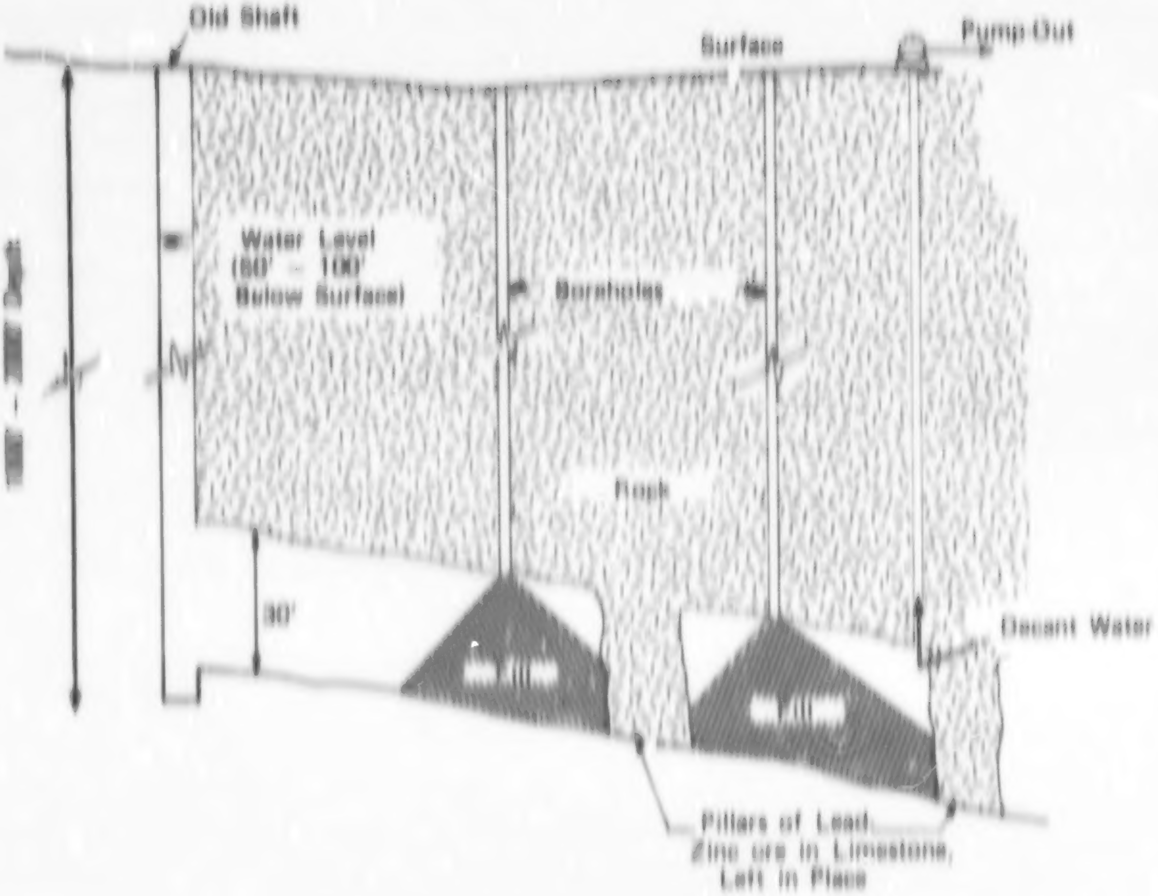

Old Shaft
Surface
Pump-Out
Water Level
(80' - 100'
Below Surface)
Boreholes
Rock
30'
Decant Water
Pillars of Lead-
Zinc ore in Limestone,
Left in Place

FIGURE V-18 BLIND HYDRAULIC FLUSHING OF ABANDONED LEAD-ZINC MINE

and spontaneous liquefaction previously discussed. However, relative to this discussion and to the specific mining conditions typical of lead-zinc underground room and pillar mines, the following impacts are projected.

- Lead-zinc mines are deep and generally underlie hard rock strata. Subsidence is not a significant impact issue for these mines.
- The mine drainage from the lead-zinc region of Southeast Missouri is alkaline. As a consequence, no impact of sulfur dioxide gas formation in these mines is expected. Likewise, if bulkheads are constructed to enable sludge disposal in active mines, corrosion potential will be lessened because of the groundwater's high pH.
- The region of the lead-zinc belt tends to exhibit moderate to major seismic risk potential. Saturated FGD sludge in abandoned mines or mined-out portions of active mines could liquefy upon deep earth vibration. However, the liquefaction potential is not considered significant in this case. If the mine is abandoned, liquefied sludge would flow freely within the confines of the mine. Because of the deep shaft's length, no sludge would discharge to the surface. In an active mine the bulkhead design would incorporate the potential for sudden loading from liquefied sludge as well as from earthquake cyclic loadings.

The U.S. Environmental Protection Agency (EPA) has proposed effluent guidelines for the lead-zinc mining industry. In active mines, FGD sludge disposal would probably result in an increased pollutant loading in the mine drainage as sludge interstitial waters leach. This may impair the mine's ability to meet effluent guidelines and discourage the mine owner's acceptance of sludge disposal in mines. In abandoned mines, pumping of mine water displaced by backfilling could create a new discharge subject to effluent guidelines. Parameters of concern include total suspended solids because of the fine grained particles prevalent in sludge and include dissolved inorganics such as copper, mercury, cadmium, and zinc, which in sludge liquor reach concentrations exceeding effluent limitations by more than an order of magnitude.

b. Environmental Impacts

The movement of groundwater through the disposed sludge mass will cause production of leachate contaminated by soluble sludge chemicals. Each year of sludge disposed in the mine would increase the total leachate flow. Because the mine is deep, strata is dense and impermeable due to confining pressures and the groundwater movement through the sludge layer is expected to be slow. As a result, leachate is likely to remain in the deep, unused portions of the groundwater regime. Thus, water/liquor displaced during disposal may present a much more serious problem than straight leachate.

c. Control Techniques to Minimize Adverse Impacts

Control techniques are the same as those discussed for underground room and pillar coal mines.

3. Limestone Mines

a. Range of Conditions Possible

Production of an active underground limestone mine ranges from 0.2 to 3.5 million short tons annually. The ore body thickness varies from 20 to 100 feet thick, with little or no overburden at an outcrop to as much as 1,000 feet of overburden for deeper seams. The ore bodies are generally horizontal, although some might slightly dip to 2 degrees.

Of all the underground room and pillar limestone mines in the United States, the seven in the Kansas City area are the most promising by the technical ranking system used. These mines are dry, located in hillsides above the water table (1). Deep wet limestone mines are not considered to be promising because limestone strata are the principal water supply aquifers in the Interior region, where most of these mines occur.

A typical mine in the Kansas City area produces about 0.9 million tons of limestone annually. The seam has an average thickness of 40 feet and has virtually no slope. About 70% of the limestone deposit is excavated, leaving pillars for roof support. The seam is accessible from the side of a hill, and FGD sludge could be placed by trucks driving directly into the mine workings. In addition to the 210 million cubic feet of mine void being created each year, these mines are reputed to have about 4,800 million cubic feet of space from past operations.

b. Impact Assessment

Technical Impacts

The technical impacts of placing sludge in worked-out portions of active or abandoned limestone room and pillar mines are minimal. The sludge would be a moist or dry solid, and the mine would be dry. Therefore, there would be no drainage requirement or involvement with effluent guidelines limitations. Generally, trucks are able to drive in and out of these mines, and subsidence is not considered an issue. Outside of the direct transfer and placement of the FGD sludge, no special handling requirements or constructions would be required.

There may be some competition for use of these mines for more profitable activities. As a result, waste disposal would receive a lower priority from the owner's viewpoint. Some of these mines are already being used for warehouse space. They are also good candidates for office space and agribusiness (e.g., chicken raising). In addition, the dry isolated nature of these mines adds to their suitability for more hazardous waste disposal than FGD sludge disposal.

Environmental Impacts

With dry sludge disposed under dry mine conditions, no leachate production or sludge drainage is expected to result from disposal in hillside room and pillar limestone mines. Therefore, no environmental impacts are projected for this case. Also, because the sludge is expected to remain dry, slide potential (which normally occurs under saturated conditions) will be minimal.

E. FGD SLUDGE AS A TAILINGS AMENDMENT

The purpose of this investigation is to determine if FGD sludge can be added to the surface of tailings from mineral processing wastes (e.g., coal refuse, mineral tailings) to enable those tailings to support vegetation. The findings indicate FGD sludge is a rather poor tailings amendment.

1. Evaluation of FGD Sludge as a Tailings Amendment

Support of vegetation is usually provided by soil, which is a mixture of a mineral substrate, air, water, and organic matter. Nutrients, macro- as well as secondary and micro-nutrients, must be present to greater or lesser degree, and the substrate must be free from toxic conditions.

Beyond these basic requirements, however, it is not possible to merely define the conditions necessary for vegetational growth (soil conditions) and then determine whether the FGD sludge and tailing combination can meet those conditions. "Soil conditions" range from the conditions of desert sand to peat bogs to bedrock outcroppings. Also, the phrase "free from toxic conditions" varies with plant species and includes, in a sense, any environmental condition which is outside of the particular niche requirements of the plant.

Tailings are highly variable. Coal refuse can contain coal, rock, bonded coal and rock, carbonaceous shale, pyrite, broken and decaying timbers, discarded machine parts and cable, paper containers, decayed brattice cloth, and grease- and oil-soaked rags. Particle sizes range from below 0.002 ppm to boulders (18). Zinc tailings in England range from very coarse to very fine with corresponding differences in water retention capabilities. Zinc residues in those tailings range from 1,370 ppm to 35,940 ppm. These same sights contained calcium levels ranging from 5 ppm to 310,500 ppm. Iron (taconite) tailings also range considerably in particle size, while pH remains about 7-8 (19). Coal refuse ranges in pH from extremely acidic (pH 2-3) to neutral or slightly alkaline (pH 7-9) (20).

Tailings have been successfully revegetated for over fifteen years. Various hardy grasses are chosen as "target" plants, and the conditions which are phytotoxic to those plants are alleviated by the addition of "soil amendments." Usually, the material added is limestone, sewage sludge, or less often, soil itself. Fly ash has been used where available because of its ability to neutralize acidic conditions, reduce bulk density, increasing moisture retention capacity, and allow greater root penetration (18).

As shown in Table IV-1, FGD sludge contains variable but significant amounts of fly ash. It also contains significant amounts of gypsum used as a soil amendment in agricultural soils to increase alkalinity and improve soil substrate (21). Gypsum is also used to decrease sodium and boron toxicity, but the gypsum must be free of toxins for any significant reduction in toxicity to occur (a condition which is not met by the gypsum in the FGD sludge) (22). The presence of fly ash and gypsum in FGD sludge has led to its consideration as a soil amendment for tailings. The following discussion presents the results of a brief investigation of this possibility.

Materials to be used as "soil amendments" are chosen on a case-by-case basis to meet the particular needs of the tailings under consideration. The potential for any material to be used as an amendment depends on its capabilities to meet these needs, i.e., to alleviate the conditions which limit plant growth. Although these conditions are highly variable, they usually involve a subset of the following:

- lack of nutrients;
- incapacity to retain moisture;
- surface instabilitiy or compacted surface;
- excess absorption or reflection of sunlight causing heat injury to plants;
- heavy metal contamination;
- excess salinity; and
- excess acidity.

The discussion below briefly assesses the potential of FGD sludge to alleviate these problems.

Lack of Nutrients

The major nutrients required by plants are phosphorus, potassium, and nitrogen. Calcium, sulfur, and magnesium are the secondary nutrients necessary for growth along with numerous micro-nutrients.

FGD sludge appears to have little or no phosphorus and a small, variable amount of nitrogen (0-50 ppm NO_3^- in sludge). FGD sludge would provide calcium (8,400-120,000 ppm in sludge) and sulfur (8,300-50,000 ppm $SO_4^=$ and 60-380 ppm $SO_3^=$ in sludge). This sulfur level may be phytotoxic, considering the amounts often present in tailings from the oxidation of pyrites. For example, the addition of gypsum to agricultural soil sometimes causes a decrease in plant growth due to excess sulfates. In citrus groves 1 ton/acre gypsum caused sulfur levels to increase to 1.43% in leaves (recommended range 0.2 to 0.3%), decreasing tree growth. The rate of application of gypsum may have been unusually high, however.

Lack of nutrients in the FGD sludge is not, however, a limiting problem in its use on tailings because of the ready availability of fertilizers which are usually applied as supplements to most tailings amendments anyway.

Incapacity to Retain Moisture

Vegetational growth is supported by soil which is 40% to 70% solid and about 20-25% water by volume in agricultural soil (although plants can be supported in widely different soil compositions). The remaining volume is air which is usually 99-100% saturated with water. The texture of the soil or the size of the soil particles determines the soil's moisture retention capacity. Because FGD sludge appears to be consistently fine in texture (e.g., 0.001-0.05 mm), it is likely to significantly increase the moisture retention capacity of those tailings which are sandy or coarse in texture (>2 mm). Tailings which are finely textured would not be benefited from the addition of sludge; these tailings tend to form compacted and easily eroded surfaces which also create moisture retention problems.

Surface Instability

Wind erosion can be a problem for vegetational growth because of the instability of the surface during seed germination and the potential for sandblasting of young plants (23). The potential for agglomeration of the tailing-sludge mixture should be investigated.

Compacted Surface

Fine tailings have a tendency to form a compacted surface which retards moisture penetration and root penetration. No information is presently available on the tendency or lack of tendency of the tailing-sludge mixture to form a crust or compacted surface once spread on the land.

Excess Surface Reflection or Absorption of Heat

Tailings tend to concentrate heat so that surface temperatures are high and the topmost soil layer loses all available moisture (23). Because the sludge seems to be consistently light in color (except when the fly ash component is particularly high), the sludge could reduce the absorption of heat by the tailings, increasing the chance of successful seedling germination.

Excess Salinity

The availability of water for plant consumption can be decreased by the development of high osmotic conditions in the plant substrate. Plants wilt, morphological changes occur (leaf curling, yellowing), and growth rate decreases. The mechanism which would account for these detrimental effects of salinity is not known; it is generally believed that the soluble salts increase the solute suction of the soil water, decreasing the uptake of water by the plants (24).

Salinity is a problem in most tailings. Tailings may become excessively saline in the recycling of processings waters. The salinity of copper mill tailings, for example, is equivalent to 2.4 atmospheres osmotic concentration (∿ 5,000 mg/liter TDS). The U.S. Bureau of Mines found that this concentration would limit initial growth of plants, although it would not significantly hinder initial germination (25). Deep mine coal wastes have been found to be "extremely salty due to the oxidation of pyrites;" for copper, zinc, lead, and uranium ores, "salinity is a common problem" (no salinity values reported) (26). Salinity has also been a problem in vegetating pulverized fuel ash (26).

Unfortunately, the salinity of the sludge also appears to be high (2,600-95,000 mg/liter TDS in FGD sludge liquors from eastern and western coals). The criteria generally assumed for irrigation water is 500 mg/liter. Water with TDS concentrations of 2,000-5,000 mg/liter is recommended only for tolerant plants on permeable soils where particular management practices are observed. Water with above 5,000 mg/liter TDS is not suitable for irrigation. Irrigation criteria are not directly applicable to the one-time application of sludge on land. They do, however, give an indication of the magnitude TDS which would be added to the already saline salts.

The ability of the sludge alkalinity to cause precipitation of soluble salts does not appear to be significant enough to decrease the salinity of the sludge-tailing mixture. Furthermore, the capability of gypsum to precipitate salts is not clear. Tests in India show that gypsum replaced exchangeable Na in sodic soils and removed soluble salts (22). Other tests, however, have not substantiated these results (27).

Acidity

While iron tailings are usually fairly neutral (7.5–8.4), most other tailings are acidic. Uranium tailings from Wyoming and Colorado had pH values of 2.3 to 4.5. Bituminous coal surface mine spoils in Pennsylvania had pH values of 2.5–4.7.

The effect of acidity is indirect. Apparently, the phytotoxicity occurring at low pH's is caused by increased availability of toxic substances. (In agricultural soils, elements necessary for plant growth can become toxic at low pH conditions.) Tailing reclamation work has generally sought to raise pH values to 6.5 or above as a prerequisite to vegetating the tailings (23). The ability of sludge to neutralize the acidic conditions of the tailings depends on the frequency of high pH conditions in the sludge. Ranges of pH for FGD sludge are 7.1–12.8 for eastern coals (fifteen observations) and 2.8–10.2 for western coals (seven observations). Although we expect that sludge is most often neutral to alkaline, the potential for eliminating acidic conditions in tailings is difficult to assess with this limited information. It would seem that two of the constituents of FGD sludge, fly ash and $CaCO_3$, would indicate a higher potential for eliminating acidic conditions than the pH ranges above indicate.

Excess Heavy Metals and Other Toxins

Tailings are usually high in metal and other toxins resulting from mineral processing (15,28, and 29). Particular toxins vary with the minerals involved. In copper tailings, for instance, copper, nickel, and zinc are high. Sulfides and sulfates are common to many types of tailings (29).

The effects of the chemical species found in tailings vary widely among plants. Zinc, copper, and nickel are usually toxic to most plants, although there are several tolerant grass species. A zinc "tolerance" based on 1:1:8 ratio for the relative toxicity interaction of Zn:Cu:Ni in soil has been suggested to be 250 ppm zinc (equivalent). This is based on an average of relative tolerance for many crops and varies according to levels of organic matter, phosphate, and pH. Similar tolerance levels have not been established for other metals and toxins. Irrigation water criteria have been established based on information on levels known to be nontoxic (not necessarily the maximum nontoxic levels).

The ability of the FGD sludge to precipitate heavy metals and other toxins does not appear to be significant. The FGD sludge itself appears to be high in heavy metals and other toxins; in some cases it may be toxic enough to create problems where none exist in the tailings. Even under a high pH condition (7.1-12.8), the FGD sludge liquor can contain relatively high levels of some metallic species. For many of the following elements, levels ranged from obviously safe to obviously toxic:

	Range in Sludge Liquor (ppm)	Irrigation Standard (ppm)
Boron	8-41	0.75
Cadmium	0.004-0.1	0.01
Manganese	<0.01-9.0	0.20
Molybdenum	0.9-5.3	0.01
Nickel	0.03-1.5	0.02
Selenium	<0.005-2.7	0.02

Many factors influence the availability of toxins to plants (adsorption, chelation, leaching). In order to assess the effect of the toxins, it would be necessary to have a particular species in mind. It would be necessary to test the particular FGD sludge to be used, the level of toxins currently found in tailings, the tolerance of the particular plants involved, and other factors such as organic matter, pH, etc. It seems safe to assume, however, that FGD sludge will not be able to alleviate existing phytotoxins problems in tailings.

In summary, the potential for use of FGD as a tailing amendment is highly variable. The particular requirements of the tailings involved must be established first, then the FGD sludge would have to be carefully tested to see if it met those requirements. To prevent creating new problems, the sludge would have to be screened for high heavy metals and other toxins, salinity, and acidity. From the information available, it seems doubtful that sludge could alleviate any problems with phytotoxins or salinity. Neither, probably, could it alleviate nutrient deficiency problems, although this is a much less serious limitation.

Acidic conditions could be neutralized if the sludge pH were high enough. The sludge could alleviate moisture retention problems and excess heat absorption by tailings. Alleviating surface instability and compaction problems by the addition of sludge needs further investigation. Further investigation, in fact, is needed in all areas which involve chemical and physical interactions of tailings and sludge.

2. Comparison of FGD Sludge to Other Amendment Alternatives

Table V-10 shows the tailing problems discussed above and the alleviating capabilities of FGD sludge, limestone, and sewage sludge.

Nutrient Deficiency

Sewage sludge usually contains significant amounts of macro-nutrients. Dried sewage sludge, for example, contains 19,900 ppm P and 4,200 ppm K (information on N not available) (30). The nutrient content of limestone is negligible.

Moisture Retention Problems

Although no specific data is available, both dried sewage sludge and crushed limestone are known to be comprised of a wide range of particle sizes. It is likely that both would increase moisture retention.

Surface Problems

Liquid sludge has been shown to increase surface stability but does little for a compacted surface (30). Limestone probably would have no effect on surface problems.

Heat Injury to Plants

The dark color of dried sewage sludge would decrease reflection of light tailings and increase absorption of dark tailings. Limestone, being light in color, would do the opposite.

Excess Salinity, Acidity, and Toxins

Limestone has been shown to precipitate salts, increase pH, and lower the availability of toxins (39). Sewage sludge has been shown to increase pH, although large amounts of sludge are needed. Sewage sludge also has been reported to decrease availability of metals by chelation.

TABLE V-10

COMPARATIVE PROPERTIES OF POTENTIAL TAILING AMENDMENTS

	FGD Sludge	Limestone	Sewage Sludge
Lack of nutrients	0	0	+
Moisture Retention Problems	+	+	+
Surface Instability	?	0	+
Compacted Surface	?	0	0
Excess Absorbtion of Heat	+	+	0
Excess Reflection of Heat	0	0	+
Excess Salinity	-	+	?
Excess Acidity	+	+	+
Heavy Metal Contamination	-	+	+

0 neither helps nor hurts significantly

+ alleviates problems to some degree

- aggravates problem

? indicates no information available

F. ASSESSMENT OF THE TECHNOLOGY

1. Handling and Transport

There are four basic modes of tranportation that could be used in moving sludge between a power plant and mine: slurry pipeline, barge, truck, and rail. Since all of these modes are technically feasible, the selection of the most appropriate mode or combination of modes should be made on the basis of a cost/benefit analysis, taking into account all operations (transfer, transport, and processing) in the transportation system.

Undoubtedly, though, certain institutional considerations will become factors in the decision process, e.g., the political and regulatory problems associated with transporting wastes across state boundaries. In many cases, institutional considerations may be the deciding factors. Such institutional factors will not be directly addressed in assessing technical or economic feasibility.

The following discussion briefly reviews the state of the technology for these four modes of transport and their applicability to FGD sludge. Various means of handling sludge in support of these transportation systems will also be discussed.

a. Slurry Pipeline

The pipeline transportation of slurry products and industrial waste materials is a proven technology, at least over short distances and for liquids of relatively low viscosity (<20 cp). However, there are very few long-distance (>20 miles), forced-main pipelines now in service for transporting slurries.

The most common uses for slurry pipelines is for transporting coal or mineral process tailings. These slurries have low viscosities at solids contents up to 50-60%. There are numerous pipelines throughout the world now handling tailing and coal slurries for distances up to 10-15 miles. Examples of long-distance slurry pipelines include the following:

- The 108-mile coal slurry pipeline in Ohio--This 10-inch line which handled 1,050 gpm of 50% slurry is no longer in service.
- The 53-mile iron concentrate pipeline in Tasmania--This 9-inch line currently handles a water/iron concentrate slurry containing up to 55-60% solids.

- The Black Mesa pipeline in Arizona--This 273-mile coal slurry pipeline handles 600 tons of coal per hour at concentrations up to 50% solids. The line is 18 inches in diameter, and the flow averages about 4,500 gpm.

Installed costs for overland pipelines of this type assuming a level, open terrain typically run $50,000-100,000 per mile for a 6- to 8-inch diameter line. Power requirements for operating such lines generally run 30-70 hp per ton-mile per day for 35-50% solids.

Application to Sludge Transport

There has been little experience in transporting slurries of FGD sludge or FGD sludge-like materials over very long distances. However, some FGD system installations are now using pipeline transport (up to 7 miles long) for moving thickened sludge (thickener underflow at 15-40% solids) to disposal/treatment areas. Such runs are typically on the order of a few hundred to a few thousand feet. Open-impeller, rubber-lined centrifugal pumps are usually used.

There has also been experience piping dredged materials over short distances, materials which are similar to FGD sludge in physical properties and consistency (silt and fine sand). For example, in beach nourishment projects it is common to transport dredged materials up to five miles. One of the new hydraulic cutterhead pipeline dredges claims a capability of pumping fine dredged materials for distances of almost ten miles.

In assessing the feasibility of slurry pipelines for long-distance transport of FGD sludge, consideration must be given to both technical design factors and overall system practicality. Technical design factors include slurry viscosity, slurry velocity, abrasion/corrosion resistance, and freeze protection.

Viscosity. The viscosity of FGD slurries depends upon the level of suspended solids, the type and size of crystals generated, and the quantity of fly ash occluded with the sludge. As shown in Figure IV-2, sludges with high levels of gypsum, fly ash, and/or residual limestone tend to have lower viscosities at a given solids concentration than sludges that are predominantly sulfite, with little or no fly ash. In order to ensure an operable pipeline, either the type of solids to be generated must be known _a priori_ (based upon projected process operating conditions) or the pipeline must be designed for a low, safe level of suspended solids that would ensure a reasonable slurry viscosity. It is reasonable to assume that, unless the sludge to be transported is almost entirely fly ash, long-distance slurry pipelines for sludge would be designed to handle no more than 25-30% solids. With large quantites of fly ash, up to 45-50% solids may be possible.

Velocity. Many of the existing coal and tailings slurry pipelines are designed for a velocity of 3-6 feet/second. Velocities on the order of 5-8 feet/second for FGD sludges would probably be required to prevent settling and pluggage of the line.

Abrasion/Corrosion. The presence of fly ash, high chloride concentrations, and frequently, low liquor pH requires the use of abrasion/corrosion resistant materials in the pipeline construction. The length of the pipeline, the level of fly ash and chloride, the slurry pH, the terrain to be covered, and the pipeline configuration will determine the most appropriate materials. In most cases, carbon steel piping is not adequate. Fiberglass, fiberglass-lined carbon steel, and rubber-lined carbon steel are all possibilities, although rubber-lined piping over long distances would probably be prohibitively expensive and may be very difficult to maintain if rubber lining failures occur.

Freeze Protection. Consideration must be given to protection against freezing of the slurry. Simple methods would include insulation and location of the pipeline underground below the freeze line. Heat tracing would be economically prohibitive. In areas where extremely cold climates exist, the cost of freeze protection may limit the length of pipelines.

The overall practicality of pipelining slurries of FGD sludge will depend not only on the cost and feasibility of the pipeline itself but also the effects of pipelining on the operation of FGD system and the disposal system. Of particular importance may be the power plant/FGD system water balance. In cases where water conservation is of concern and closed-loop operation is desirable, long pipelines may not be practical. Also, the dewatering or treatment of the sludge prior to disposal, if required, may present problems. For example, it may be desirable or necessary to admix ash with dewatered sludge either to increase the solids content or adjust the ash/sludge ratio to provide a better mix for treatment (fixation). Dewatering sludge at the mine may also create disposal problems for the filtrate, unless it is recycled to the power plant.

These factors, as well as costs for long-distance pipelines (that could run more than 25% of the installed FGD system cost), will limit the applicability of long-distance piping for sludge transport. Short-distance pipelines (<20 miles), on the other hand, may be a much more practical option.

b. Rail Haul

The hauling of FGD sludge by rail is an attractive prospect, since most large-scale industrial and utility power plants maintain in-plant rail sidings and car unloading facilities for receiving coal shipments. Where coal is delivered by unit trains and empty cars are returned directly to the coal mine, the entire roundtrip cost is already borne by the utility. Also, the amount of sludge to be returned to the mine from one power plant is always considerably less than the amount of coal delivered.

The type of rail car most amenable to sludge transport would be the bottom dump hopper cars, particularly the newer "rapid discharge, self-clearing" type. Bottom dump cars are in widespread use for coal delivery to utilities and ought to be applicable to FGD sludge transport with little or no modifications. Such cars could handle untreated FGD sludge in the form of a moist cake or treated FGD sludge either as a brick-like or soil-like material. FGD sludge as a slurry or partially dewatered (semi-liquid) material could not be handled in such cars. It would have to be either further processed by dewatering, drying, or treatment, or a rail car of different design would have to be used. In most cases, further processing either by dewatering and/or partial drying would be economically more attractive than the use of specially designed rail cars.

There would be need, of course, to add new transfer/storage facilities at both the power plant and the mine for loading and unloading the sludge. The transfer facility at the power plant for handling and loading the sludge into the rail cars would be conceptually quite simple. The sludge would be conveyed from the dewatering site to a loading dock or area above the tracks. The cars would then move below a set of feed hoppers which would direct the sludge into the cars. The sludge could be moved by front-end loaders, bulldozers, hydraulic ramps, or overhead crane. There would be need for some storage capacity at the transfer station and a number of feed hoppers in order to ensure that the unit trains would not be slowed by the sludge loading process.

Depending upon the type of sludge generated and the climatological conditions, it might be necessary to cover the storage and handling areas at the transfer station in order to prevent excessive rewetting of the sludge, which could impair sludge handling operations. In very cold climates it might also be necessary to provide for an enclosed, partially heated storage/transfer building to prevent freezing of the sludge during winter months. The problems of freezing and rewetting are primarily ones associated with the handling of untreated material. Unless the solids content of the material is marginally low, there would probably be no need for protection against rewetting of the sludge due to rainfall while in transit. Even a number of heavy rainfalls would not increase the moisture level of sludge by more than a few percent. Of more concern is the possibility of runoff or leakage of leachate from the cars due to rain. This would be unlikely unless the sludge were already too wet to absorb the additional water. In which case the simple movement and vibration of the car alone would probably cause leakage of mother liquor. Provisions would have to be made to ensure that the sludge were dry enough or that the cars would not drain. If rainfall alone could cause leakage, then the cars could be covered with removable plastic tops or tarps.

A transfer storage area analogous to that at the power plant would also have to be installed at the mine site for unloading and storing the sludge. An unloading system similar to that used for coal would probably be applicable to FGD sludge. There should be few problems encountered in unloading by either rotating car dumpers or rapid discharge, bottom dump hopper cars. With the bottom dump hopper cars, vibration of the car similar to that used for coal discharge will undoubtedly be required, particularly for discharging untreated FGD sludge. The sludge would be discharged onto a conveyor belt, which would then carry the sludge to a storage/handling facility for interfacing with the disposal operation.

As with the loading facilities, there may be need for special provisions, particularly for untreated sludges, to protect against sludge freezing or excessive rewetting prior to disposal. In fact, it may be necessary to provide for a warming house similar to that used in handling coal should the sludge freeze during shipment. In handling untreated sludges, it will probably also be necessary to provide for car washing after disposal to clean the cars prior to loading them with coal.

The facilities and equipment described above are all technically feasible and applicable to the handling and transport of both moist, untreated and treated FGD sludges. There would be no need for the development of new technology, although there may be need for some small modifications of existing equipment. It is doubtful whether a fully automated transfer facility would be practical, or even desirable, at the present time.

The cost for installing and operating such a system would obviously depend upon the quantity and type of sludge generated, the climatological conditions within which the system must operate, and the length of the rail haul. There are no existing freight rates which rail companies can apply directly to the transport of sludge, and estimates that could be prepared by rail companies even for site-specific situations could be quite speculative. A good starting point for estimating rates would be the rates for hauling sand and gravel or gypsum. However, based upon the fact that trains now in use return to the coal mines empty and that the commodity value of sludge is nil, lower rates may be negotiated. A reasonable rate over distances greater than 100 miles ought to be in the range of 1-3¢/ton-mile.

6. Truck Transport

Transport of sludge via truck is one approach now being used by utilities and is widely considered for future use where off-site disposal is required. The trucking of sludge necessitates dewatering prior to transport or the use of specially designed trucks, which would minimize the spill of contaminated or occluded liquor along public highways. Such specially designed trucks and the costs associated with transporting liquid make slurry transport economically unattractive.

One study conducted by Combustion Engineering on truck haulage of sludge involved the transport of 75 tons of settled, drained FGD sludge (50% calcium-sulfur salts, 50% ash) from the limestone scrubber system at Kansas Power and Light's Lawrence facility to Dulles Airport in Washington, D.C. (1,300 miles). Two types of trucks were used, one with a flat bottom trailer and one with a round bottom trailer. No leakage of sludge was observed, although there was drainage of excess water (liquor) through the tailgate during transport. At Dulles some difficulties were encountered with the discharge of sludge from the flat bottom trailer. Manipulation with a backhoe was required to remove all sludge from the flat bottom trailer. No difficulties were encountered in readily discharging all of the sludge from the round bottom trailer.

Similar difficulties have been experienced by some other utilities in handling and transporting semi-dewatered sludges using standard flat bottom dump trucks. In cases where the sludge has been dewatered to a moist filter cake, no such difficulties have been encountered with flat bottom dump trucks. Both dual alkali filter cake and centrifuged gypsum waste have been easily handled using front-end loaders and dump trucks at Gulf Power Company's Scholz Plant in Sneads, Florida. These solids have been readily discharged from the dump trucks without need for additional manipulation.

Therefore, in using trucks for transporting sludge either over short or long distances, it would be advantageous to produce as dry a material as possible with minimal tendency for liquefaction. For untreated materials a moist filter cake or sludge admixed with ash would be most easily handled. There should be no difficulty handling treated sludge. Loading of the trucks could be accomplished either by a hopper feed system similar to that described in conjunction with rail haul or by using front loaders or bucket crane.

Trucking of sludge would be most attractive in cases where the trucks are used for local handling of the sludge or where use can be made of coal trucks that deliver coal to the power plant. Long-distance transport of sludge by truck is generally more costly than rail and probably pipeline. Long-distance haulage rates (>50 miles) typically run between 4¢ and 6¢ per ton-mile for similar materials (e.g., sand, gypsum). Short haul rates are considerably higher but vary sharply with region and distance. More favorable rates may be negotiable for specific point-to-point local runs using dedicated trucks or empty coal trucks.

d. Barging

Barges are frequently used on the nation's rivers and intercoastal waterways for transporting both waste materials (e.g., dredge spoils) and commodities (e.g., sand, coal, lime/limestone). Where utilities receive coal by barge, barging of wastes back to the coal mine (or other mines) would be a logical alternative to overland transport. Use of empty coal barges would be preferable; however, the ability to quickly empty and clean the barges prior to reuse for coal would be a concern. Loading and unloading of standard hopper barges with dry or moist solids usually involves overhead cranes with clamshell scoops or buckets. Since this can be a time-consuming operation, it may be necessary to add barges to the fleet.

Dedicated barges and tug(s) for waste transport would provide a more flexible operation, particularly for handling thickener underflow which could be pumped directly into the barge and from the barge to the disposal site.

Barges for use on inland waterways generally carry 1,000-2,000 tons of cargo. A typical 500-MW power plant operating on high-sulfur coal with a 70% load factor would utilize one or two barges per day. Barges could be filled (and stored) for a week at a time and towed using one tug to the disposal site.

Barges purchased for dedicated waste transport service would cost $150,000 to $200,000. Barging rates could run anywhere from 0.5¢ to 1.5¢ per ton-mile depending upon location of service, tonnage handled, and transport distance. However, transfer costs could be considerably higher than those of other transport modes, particularly if solids have to be handled with overhead cranes.

2. Disposal Methods

a. Surface Coal Mines

Disposal of FGD sludge in active surface coal mines, while certainly technically feasible, does require some limitations on the physical condition of the sludge and/or disposal operation. The most practical means of disposing of the sludge would be as a slightly moist or dry solid. The sludge could then be dumped into the mined-out strip either along with or prior to replacing overburden. To handle a sludge as a slurry or as a material that exhibits a strong tendency to liquefy could present significant operational problems. The sludge could flow after being dumped either on its own or due to replacement of the overburden. In such a case, unless special precautions are taken to prevent flow (e.g., trenching of the disposal area or creation of small retainer walls with overburden), then the sludge could complicate coal removal in the following strip. Such operational considerations and potential problems are discussed in more detail in the evaluation of surface mine disposal alternative(s).

Sludge is most easily placed in a mined-out pit by truck dumping, but it is not recommended that coal haulage vehicles be used for sludge transport and placement. In some mines where rear-dump trucks are used, sludge could possibly be handled by the coal trucks on their return trip from the coal washing plant to the pit. However, such a system could lead to unacceptable delays in the coal mining operation due to the additional time for sludge loading and unloading as well as the possible need to rinse out the trucks following sludge transport to prevent contamination of the coal.

Furthermore, many mines are now using large bottom dump trucks for coal haulage. While many trucks are designed to carry up to 100 tons of coal, they have lightweight bodies, usually constructed of aluminum. Not only could the sludge corrode the aluminum, but also bottom dumping of sludge would be technically impractical. These trucks are difficult to back up and are not designed for ease of maneuvering in mine pits, and operating these trucks on a layer of sludge would be extremely difficult. In fact, operating any type of disposal truck on a sludge layer would probably be impractical. Thus, the amount of sludge that can be disposed of by truck dumping in the pit will, in most cases, be limited by the type of truck used.

Alternatively, in some mines the sludge could be dumped in the pit by the dragline or shovel returning overburden. However, this approach could seriously hamper the mining operation, since the process of digging in one pit occurs in a continuous motion using the same machine with overburden replacement in the worked-out section.

b. Underground Mines

Room and Pillar Mines

Disposal (backfilling) of waste or fill material in underground room and pillar mines has been demonstrated or practiced in both the United States and Europe. There are basically three approaches that can or have been employed: pneumatic backfilling, hydraulic backfilling (or flushing), and mechanical stowing.

Pneumatic Backfilling. Pneumatic backfilling of mine voids simply would involve blowing material through a pipeline from the surface into the vacant rooms of the mine. The pipeline could be set either in boreholes through the roof of the mine or could be mounted at an underground station, entering the mine through an existing shaft. Practically speaking, pneumatic backfilling would be done by blind injection, that is, without the aid of men underground during the backfill operation to direct the flow of material and control the distribution.

There has only been limited experience with pneumatic backfilling materials in mine voids in the United States, but considerable work has been done in European coal mines. Pneumatic backfilling has been used for the disposal of fly ash. This experience indicated that with fly ash fairly good roof contact could be achieved. Although the properties of FGD sludge are, in most cases, considerably different from those of fly ash, it is reasonable to assume that a pneumatic backfilling system could be readily designed. Of course, the backfill efficiency would differ from that attained with fly ash.

One obvious factor limiting the pneumatic conveyance of FGD sludge is that the sludge must be dry or, at worst, a moist powder. In backfilling a mined-out section of an active mine, dust control would be a major concern with such a material, as it is with any such dry stowing operation. Traditionally, "brattice cloth" (a heavy sacking material) is erected to control dust generated in pneumatic stowing of waste materials in mines. However, the wastes have generally been grainy, coarse mine tailings that may not have had the same potential for dust. Other measures may be required for dry sludge.

Consideration must be given to the type of equipment and piping used. If the sludge is slightly moist, it may tend to clog conventional equipment. If so, equipment design must be modified or the sludge pre-dried. Admixing of relatively dry, untreated sludge with fly ash may produce a sufficiently free-flowing material for pneumatic stowing. The fly ash may also impart a scouring action to keep piping and equipment relatively clean. The pressurized sludge tank and piping system, though, would have to fabricated out of abrasion-resistant material appropriate for use when fly ash containing sludges are stowed.

Hydraulic Backfilling. There has been considerably more experience with hydraulic backfilling both in the United States and Europe than with pneumatic backfilling. This method of disposal has been used to return coarse tailings from metal mines as well as coal wastes to mine voids.

In contrast to pneumatic backfilling, hydraulic backfilling can be practically accomplished either by controlled or blind injection. The distribution of material achieved depends upon the pressure head in the pipeline, the solids content of the slurry, the arrangement of the discharge piping, and the characteristics of the mine void (mine layout, coal bed slope, etc.). In some cases where there is sufficient slope of the area being filled, it may not be necessary to install bulkheads to block out the disposal area. However, in most operations utilizing mined-out portions of active mines it would have to be assumed that bulkheading would be required, particularly where the sludge is introduced through the boreholes in the mine roof.

In hydraulically backfilling FGD sludge, it is reasonable to assume that a slurry containing a minimum of 25-30% solids could be piped into the mine void. With this slurry concentration, settling in the mine void can be expected, and provisions may need to be made to pump out water/liquor runoff. If dry sludge is being slurried for hydraulic backfilling (rather than straight thickener underflow), then the collected drainage can be recycled for slurrying the sludge.

If the piping used in the backfill operation involves anything but straight vertical sections, it will have to be designed to maintain a minimum velocity of about 7 feet/second. For sludges containing fly ash, the piping and slurry handling equipment will have to be fabricated out of abrasion-resistant material.

Mechanical Stowing. Mechanical stowing of sludge can be accomplished in active mines using existing transport/conveyance equipment or equipment that can be readily adapted for use in the mine. Such an operation would generally not be economically attractive in comparison to hydraulic backfilling. However, it may be an appropriate method in certain mines such as underground limestone mines where there is ready access to mining areas. In some limestone mines it would be possible to place a moist sludge relatively easily, since a truckload could be driven into the placement area, dumped into a hopper, and stowed in the rooms.

Longwall Mines

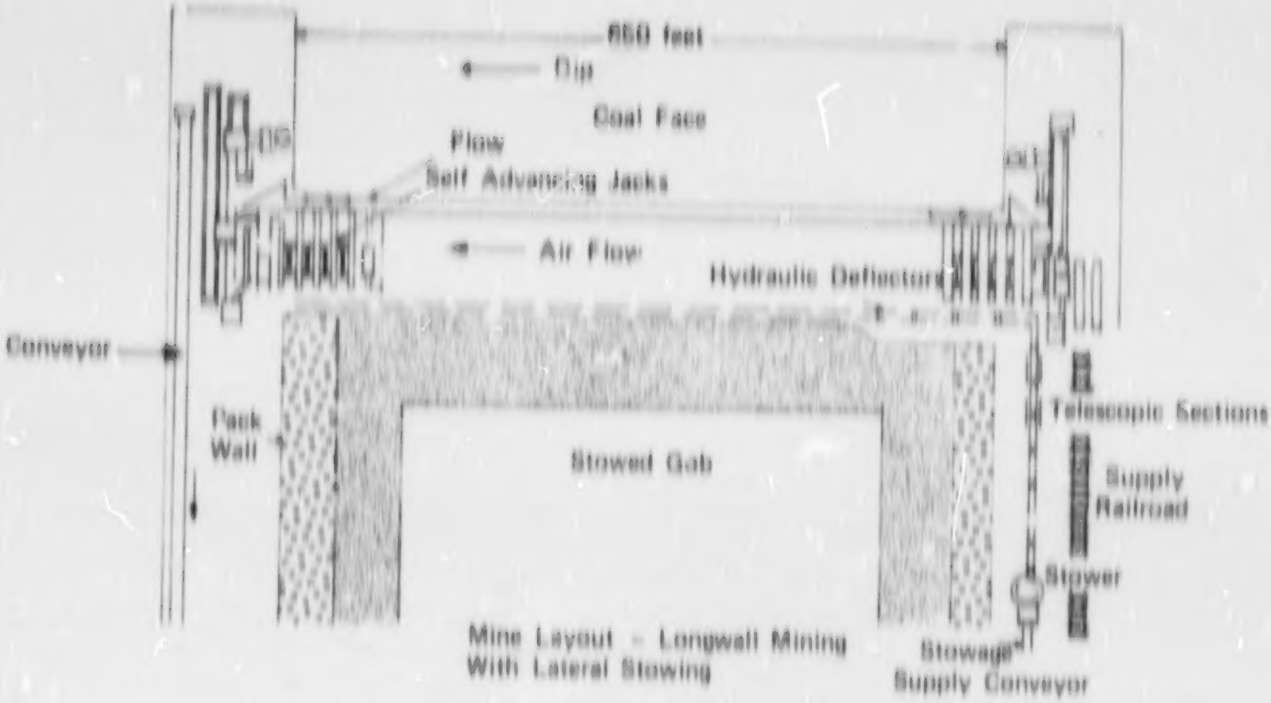
Although both hydraulic and pneumatic backfilling of waste have been used in conjunction with longwall mining, pneumatic stowing would be the preferred and perhaps only method of introducing sludge into longwall cavities. Unlike wastes that have been hydraulically backfilled in longwall mines in Europe (such as mine tailings), untreated FGD sludge does not drain to a relatively dry material even when mixed with relatively large quantities of fly ash. Thus, slurries pumped into longwall cavities could be readily forced out when the roof collapses and could cause severe problems in the coal mining operation.

Pneumatic stowing of sludge does appear to be feasible, although there may be some equipment redesign required to achieve a viable operation. Efficient, continuous lateral discharge pneumatic stowing equipment, such as that shown in Figure V-19, have been developed in Europe for handling dry materials. This equipment, though, may not be directly applicable to FGD sludge disposal unless the sludge is in the form of a dry, free-flowing solid. And such a material may result in significant dust problems, as with any such pneumatic stowing operation. However, it is reasonable to assume that appropriate handling and disposal equipment could be developed to implement an acceptable disposal system.

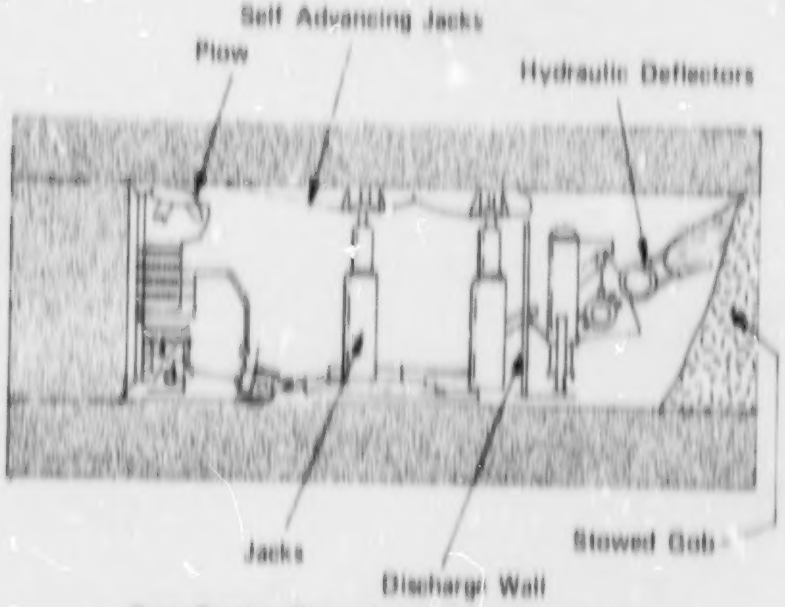
3. Monitoring Methods

a. Background

For the land disposal of FGD sludges it will be necessary to measure any physical, chemical, or biological changes that occur in the region


650 feet
Dip
Coal Face
Plow
Self Advancing Jacks
Air Flow
Hydraulic Deflectors
Conveyor
Pack Wall
Stowed Gob
Telescopic Sections
Supply Railroad
Stower
Stowage Supply Conveyor

Mine Layout – Longwall Mining With Lateral Stowing


Self Advancing Jacks
Plow
Hydraulic Deflectors
Jacks
Stowed Gob
Discharge Wall

Cross Section Through Longwall Face With Lateral Pneumatic Stowing

Source: Courtney, W.J., and Singh, Madan M., "Pneumatic Stowing: It Must be Looked At Now," *Coal Mining and Processing*, 11 (2), 1974.

FIGURE V–19 LONGWALL STOWING – LATERAL

surrounding the disposal site. In particular, the groundwater which will receive any substances leached from the sludge and which may transport these substances away from the site must be checked periodically for evidence of contamination from sludge leachate. Indication of such contamination will stem from an appropriately planned program of measurements during and after disposal coupled with a thorough knowledge of the condition of the groundwater prior to disposal. Factors such as the climate and hydrology of the area and normal effect of the physical disposal operation (such as backfilling of overburden) in the absence of the sludge must also be considered. To correlate the seasonal variations of groundwater flow and quality with climate and precipitation, it may be desirable to locate a rain gauge and record temperature near the disposal site.

For each land disposal option there are four major questions to be answered, all of which are interrelated via the hydrology and geochemistry of the disposal site:

- what species or substances to monitor;
- how to monitor these species, including sampling and measurement;
- where to monitor them, particularly with respect to placement of sampling sites; and
- frequency of monitoring.

Each of the above questions will be discussed in general in the following paragraphs and in specific terms for the individual disposal cases.

b. Species and/or Substances to be Monitored

In considering which of the many possible species to monitor as an indication of contamination of groundwater by sludge leachate, it is necessary to consider three points.

- What species are already present in the groundwater?
- What species are present in the sludge and at what concentrations relative to the groundwater?
- How are these species likely to behave during the leaching process?

Implicit in the question of what species are present in the grounwater is the question of concentration level.

For mining operations it has been recommended that background groundwater quality data should be obtained for a period of two years prior to initiating mine activities (31). For each disposal site it is imperative that measurements of groundwater quality be obtained prior to the start of any disposal operation.

Background data in the mined area would incorporate geochemical changes in groundwater attributed to disturbance and replacement of the overburden. Therefore, simultaneous measurement of groundwater upgradient of the mining area may be needed. It is also recommended that groundwater be monitored during disposal from wells upgradient of the disposal site (both within and removed from the mined area). Quarterly or bimonthly measurements should be obtained to ascertain the seasonal variation in water quality at the site.

Table V-11 gives a list of various species which are of importance to the acceptability of water for diverse uses. This listing, together with a list of the various species present or expected in the sludge (see Tables IV-1, IV-2, and IV-3) form the basis for assessing the predisposal water quality. At the very least, measurement of the unperturbed groundwater should be made for all the species listed in Table V-11.

In those cases where feasible, additional groundwater samples should be taken from an analogous operation as, for example, in an operating surface coal mine. Analysis of these samples can aid in understanding what, if any, effect the disposal operation itself has on the concentrations of the various species in the groundwater.

Because of the high degree of variability in composition, each specific sludge requires characterization and identification of significant trace metal levels. From a comparison of Table IV-3 with Table V-11, there are a number of elements likely to be of concern (e.g., Mn, Hg, Se, etc.). It is necessary to know the initial groundwater concentrations for these species. If the groundwater already has a high concentration of a specific species, the value of that parameter as an indicator of contamination is lessened.

The expected leaching behaviors of various species present in sludge have been discussed in Chapter IV. In general, sulfate, chloride, and

TABLE V-11

COMPARISON OF WATER QUALITY CRITERIA AND PRACTICAL RANGE OF MEASUREMENT METHODOLOGY

Parameter	Water Quality Criteria Levels (mg/l)[e]		Measurement Practical Range (mg/l)	Methodology[d]
	Public Water Supply	Freshwater Aquatic Life		
Biostimulants				
Dissolved Oxygen	--	5.0	0-20, ± 0.1	Polarographic probe
Ammonium	0.5	<0.02[a]	0.01-2	Automated colorimetry
Nitrate	10	--	0.05-10	Colorimetry
Nitrite	1.0	--	0.05-1	Colorimetric
Organics				
Phenols	0.001	<0.1[a]	0.005 up	Colorimetric
Cyanide	0.01	<0.005[a]	0.001-1	Colorimetric
Metals				
Ag	0.05	--	0.05-20	AA
Al	(5)[b]	--	5-1000	AA
As	0.1	--	0.002 up	AA (hydride evolution)
Cd	0.01	0.004[c]	0.001-2	AA (extraction)
Cr	0.05	0.05	0.05-100	AA
Cu	1.0	<0.006[a]	0.05-10	AA
Fe	0.3	--	0.1-20	AA
Hg	0.002	0.002 Max. Ceiling 0.00005 Avg. Max.	0.002 up	AA (cold vapor)
Mn	0.05	--	0.01-2	AA
Ni	(0.2)[b]	<0.02[a]	0.01-10	AA (extraction)
Pb	0.05	0.03	0.01-10	AA (extraction)
Zn	5.0	<0.03[a]	0.05-1	AA
Inorganic Nonmetals				
B	1.0	--	0.1-1	Colorimetry
Cl^-	250	--	20-400 5-35,000	Titrimetry Ion-selective electrode
$SO_4^=$	250	--	10-400	Nephlometric
Physical Properties				
Total Dissolved Solids	--	Minimize		Evaporation & weighing
Total Suspended Solids	--	80	20-20,000	Filtration & weighing
pH	5-9	6-9		

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[a] Approximate concentration only; criteria involve response of most sensitive biological species.

[b] Criteria for irrigation water; no public water supply criteria.

[c] Criteria for soft water (0.03 mg/l in hard water).

[d] Analytic methods listed in "Manual of Methods for Chemical Analysis of Water and Wastes", EPA [illegible], Cincinnati, Ohio, 1974; and in "Proposed Criteria for Water Quality," Vol. II, EPA, Washington, October 1973.

[e] Water quality criteria taken from "Proposed Criteria for Water Quality", U.S. EPA, October 1973.

AA = Atomic absorption spectrophotometry, utilizing auxiliary techniques such as extraction (for preconcentration) where noted sodium are less attenuated than others, and chemical oxygen demand (COD) and total dissolved solids also are not particularly attenuated (32). The latter often is related to sodium salts of the anions. Changes in the concentrations of these species (and parameters) which are least attenuated during the leaching process are the most useful indicators of the influx of sludge leachate into the groundwater. Once it is established through monitoring of some or all of these indicators that sludge leachate is present in the groundwater, then a more extensive monitoring program for other constituents previously found in the sludge liquors can be instituted.

c. Sampling and Measurement of Contaminant Species

The two major alternative approaches to the sampling and measurement of groundwater constituents are real-time, in situ measurement of components of the sample stream and removal of discrete grab (or integrated) portions of the sample stream for subsequent measurement.

The in situ measurement approach eliminates the need for sample handling (with the attendant possiblity of contamination); however, the number of different monitoring devices (or "probes") is extremely limited at this time (conductivity, pH, Cl, Na, and dissolved oxygen) and the long-term accuracy (drift) of those is generally poor. Only conductivity represents a real possibility for such monitoring and has been used frequently in similar monitoring programs. In the present study the predicted leaching behavior (transients) for all species is sufficiently slow so that continuous monitoring would not be required in order to observe the concentration changes taking place.

The general approach to be taken for the monitoring sludge disposal tests would be to obtain uncontaminated, representative samples from the aquifer or surface water and to transport these samples to an appropriately equipped laboratory for measurement. The value of accurate analysis outweighs any time savings which might be gained by in situ measurement.

A listing of measurement methods and range of application for a number of important water quality parameters is given in Table V-11. These methods are the ones which are generally used and recommended by the U.S. EPA for monitoring drinking water and wastewater. As recommended by EPA, samples should be taken into acid-washed plastic containers and filtered (except for suspended solids samples) and stabilized where necessary.

Surface water samples are usually taken using appropriate "grab" sampling procedures. Samples from subsurface aquifers are taken using air-lift or mechanical pumps made from inert materials. Samples intended for measurement of dissolved oxygen or oxidizable species (such as sulfite) are taken by mechanical pump.

d. Location of Sampling Points

The location of sampling points in the receiving waters is a function of the disposal mode being employed and the hydrology of the area. In cases such as the surface area mines, the receiving water may be a surface stream or river which can be sampled in a relatively straightforward manner. If uncertainty exists regarding the path of leachate flow from the sludge, it may be necessary to establish one or more monitoring wells across the presumed downgradient, both to establish the true flow pattern and to make certain that sufficient area coverage is provided to intercept the leachate plume. The relative merits of utilizing pumped and unpumped wells for monitoring has been discussed in published literature (31). Continuously pumped wells are useful for monitoring wider areas, but the interpretation of the resulting data is somewhat more complicated.

An extensive discussion of well placement for monitoring solid waste landfills is also available in published literature (33). Location of wells to monitor leachate plumes in unconsolidated sediment is less difficult than location of monitoring wells in bedrock. For disposal cases where sludge is used on the surface as a tailings amendment or is placed within the working pit of an active surface mine, wells may be placed in the broken up overburden, consisting of broken rock and soil which has been replaced after mining has been completed. This overburden material should initially have a fair amount of permeability to transmit water, although with time the overburden may consolidate and decrease in permeability. For disposal cases where sludge is placed in underground room and pillar or longwall mines, location of the monitoring wells will be more complex. Groundwater flow through rock with fractures and solutions must be intercepted through trial and error. A well may fail to intercept any fractures or solution cavities, thereby resulting in no groundwater yield, or it may bypass the leachate and intercept groundwater which has not been contaminated.

Mathematical modeling of the groundwater flow patterns of the individual test sites has been shown to be useful in designing the array of monitoring locations (31), but the utility of this approach obviously varies with the extent of geological and hydrological data available for each site.

e. Frequency of Monitoring

The frequency with which monitoring measurements must be made is a function of the velocity of groundwater movement and the degree to which the leachate species are attenuated or retarded during passage through the geological strata. The model of the transport of leachate species in groundwater is one which indicates a rapid increase in concentration of less attenuated species during the leaching or elution of the first pore volume of sludge, and then a gradual decrease. Some laboratory studies (Chapter IV) have shown some increase in concentration of species which are somewhat attenuated later in elution; however, the concentration change was small. Thus, during and immediately after the disposal operation, it would be necessary to monitor the concentrations of less attenuated "indicator" species rather frequently in order to obtain initial data on attenuation in "uncontaminated" soil. Because of the great uncertainties in the permeability data and calculations regarding the times required to elute "pore volumes" of sludge, the initial monitoring frequency would be at a rather high rate, possibly as little as 0.05 times the estimated pore volume transit time. The actual timing must be worked out for each case as a function of projected pore volume transit time, actual amount of sludge disposed, and desired location (distance) of monitor sites.

G. ASSESSMENT OF REGULATORY ENVIRONMENT RELATIVE TO FGD SLUDGE DISPOSAL

1. Review of Federal Legislation

a. Waste Disposal Legislation

Relevant federal legislation pertaining to waste disposal includes the Solid Waste Disposal Act of 1965, as amended, the EPA Guidelines for the Land Disposal of Solid Waste, and the recently passed Resource Conservation and Recovery Act (RCRA). The RCRA amends both the Disposal Act and the Guidelines; however, regulations and programs which it authorizes will not be promulgated or implemented until at least 18 months after enactment. Hence, this section will discuss the Disposal Act and the Guidelines, as well as the RCRA, and will describe current waste disposal practices which likely will remain unchanged until the new regulations are implemented.

The Solid Waste Disposal Act and the Guidelines for the Land Disposal of Solid Wastes

Prior to passage of the RCRA, all direct regulation of waste disposal remained at the state and local levels. The Solid Waste Disposal Act gave EPA only promotional and advisory power, while the Guidelines only recommended to local authorities procedures for waste disposal.

The Disposal Act provided for research, training, and demonstration activities related to waste disposal and authorized planning and construction grants to state and local agencies for development of solid waste disposal plants, and construction of new or improved solid waste disposal facilities. The only regulatory mandate in the Act occurred in Section 211. This section required federal agencies to comply with the solid waste Guidelines authorized under Section 209 (see below). (No comparable requirement was made of the private sector or of state and local agencies.)

The Guidelines recommended procedures for regulating the design, construction, and operation of land disposal sites. They defined solid wastes, sludges, and hazardous wastes, and recommended that hazardous wastes and sludges containing free moisture be treated as special wastes requiring case-by-case approval of the responsible agency for acceptance at disposal sites.

Neither the Disposal Act nor the Guidelines relate in any direct regulatory way to the disposal of desulfurization wastes. Because both are advisory in nature and do not provide regulatory authority, there has been and currently remains considerable variation among states and localities in the type, extensiveness, and enforcement of regulations pertaining to solid and hazardous waste disposal. The Guidelines could have promoted more uniform practices, but EPA reports that a relatively small percentage of state and local authorities appear to have utilized the Guidelines in formulating their procedures and regulations. The studies and grants provided under the Disposal Act heightened the awareness of many states of solid and hazardous waste problems and in some states resulted in departmental reorganization and improved regulations and enforcement, but in many other states there was little change.

Desulfurization waste may be determined to be hazardous due to the heavy metals present in its leachate, although this determination has not yet been made. The disposal and management of hazardous wastes under the Disposal Act and the Guidelines has remained a problem for almost all states, including most of the states which have established laudable systems for managing and disposing of nonhazardous solid waste. State needs for effective hazardous waste management include an enforceable definition of hazardous waste, a comprehensive approach to groundwater protection including procedures for analyzing leachate and attenuation effects, and a system for regulating the transport of wastes from the point of generation to the disposal site.

The Resource Conservation and Recovery Act (RCRA)

The Resource Conservation and Recovery Act was signed into law in October 1976. The Act creates federal and state regulatory authority for both solid and hazardous wastes. Federally approved solid waste management plans are mandatory for each state, while federally authorized state hazardous waste programs are optional. In all states without such programs the federal government will regulate hazardous wastes.

EPA's Office of Solid Waste Management has indicated that desulfurization sludge likely will be considered hazardous waste under the Act. In contrast, solid waste personnel in Pennsylvania, Illinois, and Kentucky indicate that based on leachate constituents they would not classify desulfurization sludge as hazardous. Resolution of this difference must await promulgation of regulations authorized in Section 3001 which will identify the characteristics of hazardous waste and list particular hazardous wastes. Large quantities of FGD sludge will be generated and will require disposal. Because there is question regarding the nature of desulfurization sludge, the following discussion covers provisions of the Act which pertain to both hazardous and nonhazardous wastes.

Key definitions in the Act which pertain to desulfurization waste disposal include hazardous waste, sludge, and solid waste. Relevant sections of these definitions follow:

- hazardous waste--"a solid waste, or combination of solid wastes, which because of its quantity, concentration, or physical, chemical, or infectious characteristics may...pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed."
- sludge--"any solid, semi-solid, or liquid waste generated from an ...air pollution control facility..."
- solid waste--"any garbage, refuse, sludge from an...air pollution control facility...including solid, liquid, semi-solid, or contained gaseous material..."

Section C, Hazardous Waste Management, authorizes the Administrator of the EPA to establish a hazardous waste management system and provides for authorization of state hazardous waste programs in states where programs meet the requirements of the Act. Sections 3001 through 3006 require that within 18 months after enactment the Administrator shall:

- develop and promulgate criteria for identifying characteristics of hazardous wastes;
- promulgate regulations identifying characteristics of hazardous waste and listing various hazardous wastes;
- promulgate regulations which establish standards for generators and transporters of hazardous waste and performance standards for owners and operators of waste facilities;
- promulgate regulations which require that each owner/operator obtain a permit;
- promulgate guidelines to assist states in the development of state hazardous waste programs.

These requirements are discussed in the following paragraphs.

Development of specific and/or quantitative criteria and regulations which identify characteristics of hazardous waste should provide federal and local authorities with long needed guidance in the management of hazardous wastes. Although EPA personnel have not yet determined a comprehensive approach to development of such criteria and regulations, they have initiated work on two relevant, related procedures, a Standard Leaching Test and a Standard Attenuation Procedure.

The regulations which establish standards for generators and transporters of hazardous waste must include requirements respecting recordkeeping, labeling, and reporting practices and use of a manifest system. Regulations which establish performance standards for owners and operators of facilities must include requirements respecting: (1) treatment, storage, or disposal of waste by methods satisfactory to the Administrator; (2) the location, design, and construction of hazardous waste facilities; and (3) contingency plans for effective action to minimize unanticipated damage from treatment, storage, or disposal of hazardous waste.

The regulations regarding permits to operate waste facilities must require that permit applications provide estimates of quantities and concentrations of hazardous wastes to be disposed of and technical descriptions of the disposal site.

Guidelines developed by EPA will assist states in developing hazardous waste programs. States will be "authorized to carry out such program(s) in lieu of the Federal program when such programs are equivalent." In accord with this, EPA has indicated that these guidelines will include requirements that state programs, as a minimum, must comply with all the federal criteria, regulations, and standards promulgated under the Act.

The Act does not require promulgation of uniform groundwater criteria for monitoring and site selection. Although such criteria would be desirable from the perspective of enforcement, they cannot be readily established due to seasonal variations and other variations in groundwater composition upgradient of disposal operations which therefore affect downgradient compositions. Hence, monitoring and site suitability judgments must be made on a site-specific basis.

Finally, regarding hazards waste, Section 3006 discusses the procedures and timing for implementation of state hazardous waste programs. Guidelines to assist states in the development of such programs must be promulgated by the Administrator within 18 months of enactment. States may then submit an application for program authorization which must be approved or disapproved by the Administrator within 180 days of submittal. Alternatively, states which have in existence hazardous waste programs pursuant to state law within 21 months after enactment may be granted "interim authorization" to carry out such programs in lieu of the federal program for 24 months, if the state program is substantially equivalent to the federal program.

Subtitle D, State or Regional Solid Waste Plans, requires that each state establish and implement a solid waste management plan which has received approval of the Administrator as meeting the requirements of the Act. The governor of each state is authorized to identify regions for solid waste management, identify an agency to develop and implement the State Plan, and identify which solid waste functions will be the responsibility of the state and which will be the responsibility of regional or local authorities.

The following are areas which the guidelines must address and which are important for effective planning for and regulation of desulfurization waste disposal:

> "the varying regional, geologic, hydrologic, climatic, and other circumstances under which different solid waste practices are required in order to insure the reasonable protection of the quality of the ground and surface waters from leachate contamination, the reasonable protection of the quality of the suface waters from surface runoff contamination, and the reasonable protection of ambient air quality;"
>
> "characteristics and conditions of collection, storage, processing, and disposal operating methods, techniques and practices, and location of facilities where such operating methods, techniques, and practices are conducted, taking into account the nature of the material to be disposed;" and
>
> "the constituents and generation rates of waste."

In summary, the RCRA provides comprehensive regulatory authority at the federal level in the area of hazardous and solid waste management where previously there was none. Under the Solid Waste Disposal Act, the federal government had advisory and promotional powers in waste disposal matters but no regulatory power. Under the RCRA the federal government is authorized to provide direction and continuity in waste management. To this end, the Act provides for the establishment of criteria for identifying hazardous waste, creates an institutional framework for federal and state planning, authorizes the federal government to provide the states with guidelines and requirements for development of state programs, and authorizes comprehensive regulatory promulgation at both the federal and state level with regard to hazardous and solid waste.

Further, the Act provides unquestionable coverage for desulfurization waste disposal through very specific definitions of sludge and solid waste and through a broad definition of hazardous waste. The definition of "sludge" specifically includes solid, semi-solid, or liquid waste generated from an air pollution control facility, while "solid waste" is defined to include sludge from such a facility. "Hazardous waste" is defined as a solid waste which poses hazards to human health or the environment when improperly treated, stored, transported, or disposed of. EPA currently believes that desulfurization waste will be considered hazardous waste, although the final determination has not been made. However, should the regulations authorized under Section 3001 for identifying characteristics of hazardous waste and the listing of hazardous wastes ultimately indicate such wastes to be considered solid but nonhazardous, the definitions of "sludge" and "solid waste" insure that coverage will still be provided by the Act.

Of particular importance to desulfurization waste disposal operations are the sections providing for protection of groundwater quality. With regard to hazardous waste, Section 3004 requires performance standards applicable to disposal site owners and operators as may be necessary to protect human health and the environment. Such standards must include requirements for "disposal by practices...satisfactory to the Administrator." With regard to solid waste, Section 4002 requires that the guidelines for state plans which the Administrator promulgates shall consider the hydrologic, geologic, and other circumstances required to insure "protection of the quality of the ground and surface waters from leachate contamination." Based on these sections, it can be assumed that the performance standards and the state solid waste plans will require groundwater protection.

Finally, although the Act provides adequate legal protection of the environment by addressing groundwater degradation and by providing an institutional framework for planning, regulatory implementation and enforcement, the technical aspects of providing protection can only be handled on a site-specific basis.

b. Water Legislation

The Dam Safety Act, the Federal Water Pollution Control Act Amendments (FWPCA), and the Safe Drinking Water Act have been included for assessment in the area of water legislation. Focus of concern with the Dam Safety Act is the anticipated safety and environmental regulation of all dam structures, including the impoundments likely to be part of certain desulfurization waste disposal operations. The primary concern with the FWPCA and the Safe Drinking Water Act is their approach to protection of the nation's waters, particularly groundwater, from pollution.

The Dam Safety Act required initial inspection and inventory of all dams of specified size and a subsequent report to Congress recommending legislation and regulatory structures to assure public safety from dam disasters. To date, the inventory has been completed, and all federal dams have been inspected. (No appropriation of funds for inspection of non-federal dams was made.) The report will be submitted to Congress within a few weeks. Although details of the report have not been disclosed, the Corps has indicated that the report will recommend a comprehensive national Dam Safety Program (which includes regular dam inspection) and will provide a model state law and model inspection guidelines for use by the states in establishing state programs. The report also will recommend appropriate roles for the states and the federal government. The Corps has indicated further that the laws and regulations which eventually will be promulgated with respect to dam specifications and inspections likely will apply to most mine site impoundments.

Both the FWPCA and the Safe Drinking Water Act authorize protection of the nation's waters. Together, they employ a variety of approaches to pollution control. Interpretations to date have produced even further variations. Thus, assessing the adequacy of these laws in protecting the environment is a complex task, and this discussion focuses on standards and criteria which protect surface waters through regulation of discharges from point sources and protection of ground and surface waters through regulation of seepage (nonpoint source). Point source regulation presents a simpler problem, as the FWPCA provides authorization for effluent standards as influenced by the water quality of the receiving stream under several sections, including 301, 302, and 402. Regulation of seepage discharges (excepting seepage from deep well injection, discussed below) is not directly authorized in either act, nor are standards or criteria applicable to such discharges provided for. However, EPA has indicated that sections 208 and 402 of the FWPCA and Sections 1424 and 1431 of the Safe Drinking Water Act may be interpreted to regulate such discharges.

Following is a summary of the potential relevance of each of the above sections to FGD sludge disposal operations.

Federal Water Pollution Control Act Amendments (FWPCA), PL92-500

- Section 301--"There shall be achieved...effluent limitation of point sources other than public-owned treatment works." Point source effluent limitations for mines have been prepared and are currently under review. The limitations regulate all point sources on mine property. They would apply to desulfurization waste disposal operations, as most operations will discharge into existing mine pits or create new point sources such as discharges from pumping out of abandoned underground mines or from pumping collected groundwater, seepage, precipitation, and surface runoff from surface mine pits.
- Section 302--"authorizes effluent limitation to enable attainment or maintenance of that water quality in a specific portion of the navigable waters which shall assure protection of public water supplies..." Although protection of public water supplies could be interpreted to include protection of groundwater to date, development of effluent limitations has considered only the quality of receiving surface waters. When the water quality of the receiving stream meets the standards for its designated use, the federal effluent guideline limitations are applied. When the water quality of the receiving stream does not meet standards for its designated use, effluent limitations more stringent than the federal guideline limitations are applied.
- Section 402--authorizes under the National Pollutant Discharge Elimination System (NPDES) permits "for discharge of any pollutant" which meets all applicable requirements of the Act. To date, EPA

focus largely has been limited to protection of surface water quality, and permits have been issued for discharge to surface water only. However, EPA has indicated that future interpretations may require NPDES permits for discharges to groundwaters as "discharge of any pollutant" can be interpreted to include as receivers both surface and groundwater.

- Section 208--Subsection (b)(2)(K) requires that any areawide waste treatment management plan shall include "a process to control the disposal of pollutants on land or in subsurface excavations within such area to protect ground and surface water quality." Most areawide plans currently are being prepared. EPA has indicated that, although the Act has been interpreted primarily as a surface water law to date, future interpretations of Section 208 likely will broaden to include groundwater protection. Seepage resulting from mine disposal of desulfurization waste could be regulated through the areawide plans under Subsection (b)(2)(K), although the primary vehicle for regulation is expected to be the RCRA discussed previously.

Safe Drinking Water Act, PL93-523

This Act authorizes national primary and secondary drinking water regulations applicable to public water systems to protect the public health and welfare. The regulations must specify contaminants, maximum contaminant levels, and critera and procedures to assure a supply of drinking water which complies with such levels. To date, procedures for the assurance of such a supply have not directly included protection of groundwater from seepage except in land application of municipal wastewaters.

Based on discussion with the EPA Office of Water Supply, only Sections 1424 and 1431 of the Act may be interpreted as applicable to desulfurization waste disposal in mines. Section 1424, "Interim Regulation of Underground Injections," (Subpart (e)) states:

> "If the Administrator determines...that an area has an aquifer which is the sole or principal drinking water source for the area and which, if contaminated, would create a significant hazard to public health...no commitment for Federal financial assistance...may be

> entered into for any project which the Administrator determines may contaminate such aquifer through a recharge zone so as to create a significant hazard to public health..."

This section could be used to prohibit disposal in specific mines when federal funding is involved, if leaching and site analyses indicate probable groundwater contamination.

Section 1431, "Emergency Powers," authorizes the Administrator to "take such actions as he may deem necessary" to protect the health of the public upon receipt of information that a contaminant is present or is likely to enter a public water system which may present an imminent and substantial endangerment of the public's health. Actions which the Administrator may take include: "(1) issuing such orders as may be necessary to protect the health of persons who are or may be users of such system.. and (2) commencing a civil action for appropriate relief, including a restraining order or permanent or temporary injunction." This section provides broader coverage than Section 1424 in that the Administrator's authority is not limited to situations involving federal funds but extends to all situations where contaminants may endanger public water systems. Regulation of existing FGD sludge disposal may be covered under this section, although new disposal operations are expected to be covered under the RCRA, discussed previously.

The Office of Water Supply has indicated that no other sections of the Safe Drinking Water Act are being interpreted to apply directly to desulfurization waste disposal. Until relatively recently, some questions remained regarding applicability of Part C, Protection of Underground Sources of Drinking Water, which addresses underground injection control programs. EPA has recently completed the regulations for state control programs (authorized in Part C, Section 1421) and indicates they are not intended to include mines of any type. The regulations are limited to deep wells which are defined as openings with "depth greater than surface diameter."

In summary, both the FWPCA and the Safe Drinking Water Act contain authority to protect groundwater from seepage, but such authority has been rarely exercised to date. EPA's regulatory efforts under the FWPCA have been limited primarily to discharges to surface waters due to the cost-effectiveness of regulating the point sources first and the technical complexities inherent in regulating underground discharges. Only recently has attention been focused on regulating groundwater pollution.

Interpretation of the FWPCA as a groundwater law (as well as a surface water law) results in comprehensive legal coverage for all aspects of desulfurization disposal operations relevant to water pollution. However, truly effective regulation of seepage under the Act requires improved technical capability, as discussed in the section of Waste Disposal Legislation.

In the Safe Drinking Water Act, authority to regulate seepage in emergency situations or when federal funds are involved exists under Sections 1424 and 1430. In the FWPCA, authority to regulate seepage exists under Section 208, which provides for areawide waste treatment management plans, and Section 204, which provides for NPDES permits. Based on discussion with EPA, it appears that future regulation of seepage from waste disposal in mines will occur primarily under Section 208 through the areawide plans.

c. Health and Safety Legislation

Federal regulation of health and safety is shared by two agencies, the Mining Enforcement and Safety Administration (MESA) and the Occupational Safety and Health Administration (OSHA). The specific authority of each agency with regard to mines was clarified in 1974 in a jointly issued Memorandum of Understanding. The Memorandum defines mining and milling activities, and states:

> "MESA has enforcement authority for employee safety and health in mines and mills. OSHA has safety and health enforcement authority in processes beyond mines and mills."

Despite the Memorandum, MESA officials indicate that there continued to be specific cases where the authorities of MESA and OSHA need clarification. In resolving these cases, MESA authority frequently is considered limited to the "health and safety of miners working on mine property."

In addition to federal regulation, many states maintain a substantial regulatory role in mining operations and mine health and safety. States frequently enforce federal standards and complementary state standards, and promulgate and enforce additional standards and regulations in areas not addressed by the federal government, such as subsidence, mine drainage, and reclamation.

Included in this assessment are three acts which provide for health and safety regulations by MESA and OSHA, namely the Metal and Nonmetal Mine Safety Act, the Federal Coal Mine Health and Safety Act, and the Occupational Safety and Health Act, and the health and safety standards and proposed amendments issued by MESA pursuant to these acts. (OSHA standards and regulations have not been included due to their extensive detail and questionable relevance to this study.)

The MESA health and safety standards regulate many activities and conditions of both underground and surface mine areas, including general air quality and ventilation; dust and noise levels; sampling methods and procedures; material handling and storage; use of equipment; and loading, hauling, and dumping. The Safety Standards for Surface Coal Mines and Surface Work Areas of Underground Coal Mines include new adopted amendments pertaining to refuse piles and impoundments. Disposal of desulfurization wastes in mines will likely necessitate creation of stockpiles and impoundments similar in material and engineering properties to those addressed in the amendments.

A detailed assessment of the adequacy of the existing federal health and safety legislation to protect miners and the public from any ill effects of mine disposal of desulfurization wastes is not presented here. Use of mines for disposal of desulfurization wastes would present regulatory bodies with a new situation not anticipated when current regulations and standards were established. Although there are areas of regulation which can be interpreted to apply to desulfurization waste disposal should such disposal near implementation, the entire spectrum of health and safety regulations would require thorough assessment. Considerable additions and modifications likely would be required. MESA officials have stated that clarification of authority regarding regulation of mine disposal would need considerable study. Consideration would minimally include the respective roles of MESA, OSHA, and other existing or new federal authorities, and the role of the various state governments.

In summary, the current health standards and regulations of particular importance to disposal of FGD wastes include those pertaining to dust (standards), airborne contaminants (threshold limit values), noise, and sampling and measurement procedures. Standards for surface and underground coal mines are currently as follows:

- dust--average concentration of respirable dust of 2 mg/cubic meter of air or less;
- airborne contaminants--the threshold limit values adopted by the American Conference of Governmental Industrial Hygienists in 1970; and
- noise--maintenance of noise level during each shift at or below the following permissible noise exposures.

Duration per Day (hours)	Noise Level (dBa)
8	90
6	92
4	95
3	97
2	100
1-1/2	102
1	105
3/4	107
1/2	110
1/4 or less	115

Additional health regulations will likely be required in certain other areas, and some of the above standards would probably be modified.

Current safety standards and regulations of particular interest include those in the area of surface installations (including equipment, materials storage, stockpiling, reclaiming, refuse piles, and impounding structures), ground control, loading and haulage, roof support, and ventilation. Existing safety regulations cover the primary areas of operation of desulfurization waste disposal. Thus, safety standard changes would be primarily adaptions rather than additions.

e. Transportation Legislation

Relevant federal legislation in the area of transportation includes the new Hazardous Materials Transportation Act, the Transportation of Explosives Act, the Hazardous Cargo Act, and the Ports and Waterways

Safety Act. These acts authorize numerous regulations governing all modes of transport--motor carriage, rail, water, pipelines, and air.

Although each act is addressed to materials of a hazardous or dangerous nature, the acts vary in their definition of hazardous and dangerous materials. In certain cases, particularly the Explosives and Cargo Act, the definitions create doubt as to applicability to desulfurization wastes. Additional questions of applicability stem from the remaining chemical and physical questions regarding the hazardous nature of desulfurization wastes.

However, the Hazardous Materials Transportation Act, which will effectively replace these two acts in time, appears to possibly be applicable to desulfurization wastes. The Act regulates hazardous materials defined as follows: "substances or materials in a quantity and form which may pose an unreasonable risk to health and safety or property when transported in commerce." Further, the Act defines commerce to include the transport of desulfurization waste under consideration. Commerce is defined as "trade, traffic commerce or transportation, within the juridiction of the United States, (A) between a place in a state and any place outside of such state, or (B) which affects trade, traffic, commerce, or transportation described in clause (A)."

An assessment of the adequacy of the regulations pursuant to these acts is beyond the scope of this effort due to their extensive numbers and technical detail. However, in summary, the four acts provide for regulation of all modes of transportation under consideration; desulfurization wastes are a type of material covered by the acts; and the transport of similar materials in slurry, solid, and semi-solid form is a common longstanding activity of commerce. Hence, transportation of desulfurization wastes likely will not require new regulations or modification of the existing administrative structure. The effectiveness and adequacy of the existing structures and regulations can be further assessed, as needed, by review of their historical adequacy with similar materials in the various modes of transportation.

2. Review of State Regulations

At the state level there are a number of statutes which might affect the disposal of FGD sludge in mines. The extent to which the laws and regulations of the various states might affect FGD sludge disposal will depend on the interpretations of the various enforcement agencies. As mentioned previously, no states have been identified that have statutes specifically directed toward regulating the disposal of FGD sludge in mines.

The existing statutes differ for each state. It is impossible within the scope of this report to cover for each state the laws and regulations which might impinge on FGD sludge disposal in mines. Therefore, the laws of one state, Pennsylvania, have been examined. Pennsylvania is considered to be representative of states with potential for FGD sludge disposal.

- It is an industrialized state and is confronted with disposing large amounts of FGD sludge.
- In certain areas, land suitable for surface disposal of sludge is limited.
- It has many active and abandoned surface and underground mines which might be used for sludge disposal.
- Stowing of materials in abandoned mines has occurred to limit subsidence and acid drainage formation.
- Its mining laws and regulations are comprehensive and deal with mining conditions similar to those found in other mining states.

In Pennsylvania, statutes in three areas, mining, water, and solid waste, may apply to FGD sludge disposal in mines. The specific statutes, as amended, are as follows.

Mining

Pennsylvania Bituminous Coal Mine Act, Act 339, July 17, 1961
Act 346 (relating to anthracite coal mines), November 10, 1965
The Coal Mine Sealing Act of 1947, Act 490, June 30, 1947
Sealing Abandoned Bituminous Coal Mines, Act 55, May 7, 1935
Surface Mining Conservation and Reclamation Act, Act 418, May 31, 1945

Water

The Clean Streams Law, Act 394, June 22, 1937
Pennsylvania Industrial Wastes Regulations, Title 25, Chapter 97, September 2, 1971
Pennsylvania Mine Drainage Permits Regulations, Title 25, Chapter 99, September 2, 1971

Pennsylvania NPDES Permit Regulations, Title 25, Chapter 92, September 28, 1973

Solid Waste

Pennsylvania Solid Waste Management Act, Act 241, July 31, 1968

Pennsylvania Solid Waste Regulations, Title 25, August 2, 1971

Some of the mining statutes are concerned with protecting the mine workers, while others are concerned with protecting the environment. Worker-oriented acts include the Bituminous Coal Mine Act and Act 346 (relating to anthracite coal mines) which focus on maintenance of mine conditions that insure miner health and safety. Environment-oriented acts include the Coal Mine Sealing Act of 1947 and the Sealing Abandoned Bituminous Coal Mines Act, both of which require the sealing of abandoned mines in order to control acid mine drainge. Also, the Surface Mining Conservation and Reclamation Act seeks to guarantee appropriate reclamation of surface mining areas by requiring detailed reclamation plans and posting of bonds.

The water laws and regulations focus on protection of both surface and groundwaters by requiring permits for any discharges or activities which may affect those waters. The Clean Streams Law and the NPDES Permit Regulations provide for control of industrial waste discharges, related seepage, and discharge from mines. The Mine Drainage Permit Regulations provide additional control of mine discharges by setting discharge limitations on acid, iron, pH, and other constituents of drainage such as aluminum, sulfates, and manganese. Finally, the Industrial Wastes Regulations prohibit the disposal of inadequately treated wastes in mines.

The Solid Waste Management Act and subsequent regulations focus on protecting land and water resources by requiring permits for all land disposal, including disposal in mines, of solid and hazardous wastes. The Solid Waste Management Act requires a permit for transport of wastes to mines, approval of the Department of Environmental Resources, the Department of Commerce, and the county commissioners for waste disposal in mines, and a plan and bond for landscape restoration following such disposal. The Solid Waste Regulations require that a permit be obtained from the Department of Environmental Resources before any land can be used for either solid or hazardous disposal. In issuing a permit for either solid or hazardous wastes, the Department will consider factors related to site selection, storage, operations, reclamation, and transportation.

The assessment of the Pennsylvania statutes has been performed in much the same way as that of the federal statutes. The following is a summary of the assessment.

- The Department of Environmental Resources will have lead responsibility for regulating FGD sludge disposal in mines. The primary regulating statutes are administered by the Bureau of Mine and Occupational Safety, the Bureau of Water Quality Management, and the Bureau of Land Protection and Reclamation.
- The regulating statutes do not specifically address FGD sludge and sludge disposal operations, thus requiring individual interpretation. However, regardless of interpretation, collectively the statutes appear to provide coverage for all aspects of FGD disposal. On-land FGD sludge disposal is already being regulated in Pennsylvania.
- Specific areas of the regulating statutes which might be interpreted as covering sludge disposal include those which:
  - prohibit the dumping of offensive material into coal mines;
  - prohibit the disposal of inadequately treated wastes into underground mines;
  - require that a permit be issued before any land can be used for solid waste disposal;
  - require a reclamation plan be approved by the state before any surface mining operation is permitted; to assure that the reclamation is carried out according to the approved plan, a bond must be deposited with the state (such a reclamation plan and bond could be required for disposal of FGD sludge in surface mines; alternatively, disposal of FGD sludge could be integrated into surface mine reclamation plans);
  - require the sealing of mines in order to prevent acid mine drainage once mining operations have ceased; and
  - regulate and protect water quality (these not only include regulations related to point and nonpoint source mine discharges but also regulations which prevent unauthorized continuous or intermittent contact of a solid waste with groundwater).

Pennsylvania has become aware of certain problems in using its existing regulations to control FGD sludge disposal. Consequently, the Department of Environmental Resources is considering regulatory amendments needed in order to permit an orderly and environmentally sound disposal of FGD sludge. For example, mine sealing requirements may need modification to accommodate FGD disposal. Additional required amendments may be clarified by a pilot field program currently being conducted under an EPA grant which would evaluate the disposal of FGD sludge in underground mines. The proposed program would Pennsylvania and placing them in a deep inactive mine within a reasonable distance of the source power plants.

H. CONCLUSIONS AND RECOMMENDATIONS

1. Technical/Environmental Considerations

The overall conclusion from this assessment of the disposal of FGD sludges in mines is that while promising from both a technological and an environmental standpoint, such disposal operations can result in significant environmental impacts and each proposal for FGD sludge disposal must be assessed on a case-by-case basis to determine the magnitude and acceptability of these impacts. The fate of the sludge and the extent of the environmental impacts will depend primarily on the geology of the particular disposal site and on the specific characteristics of the sludge but also on the indigenous quality of receiving groundwaters and potential pathways to surface waters.

Specific conclusions of the assessment are as follows:

- There is sufficient available space in the United States being generated annually in active mines for disposal of all FGD sludge. Individual coal mines in most cases have space available to dispose of at least the amount of sludge produced from the coal extracted.

  Mines employing surface stripping or underground conventional room and pillar operations are the most promising because of their accessibility and availability of space. Open pit mines are generally not promising because use of the space would hinder access to mineral reserves. Underground mines employing caving (by longwall, pillar robbing, or stoping) have limited promise because they lack available space. By production and available space, the most promising categories of active mining for accepting sludge are ranked as follows:

1. surface coal mining;
2. underground room and pillar coal mining;
3. underground room and pillar limestone mining;
4. underground room and pillar lead-zinc mining;
5. underground room and pillar salt mining; and
6. underground longwall coal mining.

- Placement and handling techniques for FGD sludge disposal in both surface and underground mines are available and have been demonstrated for disposal of other materials in mines (i.e., coal refuse), although the techniques may require modifications for application to FGD sludge disposal. There is the potential for significant disruption of ongoing mining operations due to the volume and physical properties of sludge to be handled. One potential physical impact of concern is liquefaction of the sludge either during disposal operations or after disposal is completed. However, sound engineering design of sludge placement, proper site selection, and constraints on sludge properties can control such impacts.
- The major potential adverse chemical impact of FGD sludge disposal in the vicinity of mining is increased constituent loadings (especially sodium and calcium chlorides and sulfates) to the mine drainage discharge. In areas removed from the influence of mine drainage pump-out the principal potential adverse chemical impact of FGD sludge is leachate contamination of groundwater. Leachate concentrations for treated and untreated sludges are generally expected to be within the ranges of concentrations of the chemical constituents in FGD sludge liquors for hundreds

of years due to the slow movement of groundwater. However, the significance of the impact on the groundwater will depend importantly on the quality of the groundwater and the total quantity of leachate produced as well as its concentration. This must be evaluated on a case-by-case basis relative to potential contaminant contributions to downgradient water supply wells and surface waters. In some cases the quality of the leachate would be no worse, and possibly better, than existing mine drainage, at least with regard to acidity and total dissolved solids (TDS).

- The generation of sludge leachate will be site-specific, with the greatest amounts produced when sludge is within a groundwater regime of high transmissivity (having a steep hydraulic gradient and high permeability). Attenuation of FGD sludge leachate is also site-specific, with the least attenuation in acidic groundwater environments having soil and rock of limited ion exchange capacity. Integrating these two factors, ranking of mining categories on a national perspective (in order of the most promising):
  1. underground limestone and coal room and pillar mines above the water table;
  2. coal surface area mines (Interior and Western);
  3. coal surface contour mines (Eastern);
  4. lead-zinc underground room and pillar mines; and
  5. coal underground room and pillar, and longwall mines within the water table (Eastern and Interior).

  Note: Salt mines were not specifically addressed within the scope of this study, even though they could receive the highest ranking. Salt mines have generally been assigned a higher priority with regard to the disposal of wastes, e.g., hazardous radioactive wastes.

- The generation of sludge leachate is also sludge-specific with decreasing amounts occurring with decreasing sludge permeability (especially through compaction or chemical treatment). The concentrations of constituents in leachate is also sludge-specific, with concentrations tending to decrease as alkalinity increases, fly ash content decreases, and inorganic constituents originally present in coal decrease, i.e., chloride and trace metals.

- Discharge of sludge leachate to surface waters can adversely affect aquatic life by the addition of biocumulative trace metals. In the case of sludges containing sulfite, there is the potential toxicity of dissolved sulfite itself as well as the potential depletion of dissolved oxygen due to the sulfite.
- In surface mines, control techniques to minimize groundwater contamination include decrease of sludge permeability through compaction or chemical treatment and placement of sludge outside the groundwater reservoir through modified disposal operations. In underground mines, the primary control technique is chemical treatment.
- The state-of-the-art of site monitoring and analytical techniques to predict and assess impacts is adequate for FGD sludge disposal. The general location of monitoring sites must be based upon geologic field surveys in order to develop appropriate background and leachate data.
- In underground mines, FGD sludge placement results in the potential benefits of lessening acid drainage formation and long-term subsidence, primarily by sealing exposed coal against air exposure which leads to pyritic sulfur oxidation and also leads to pillar deterioration.
- FGD sludge provides little potential as an amendment to mine tailings for enhancing vegetative growth. In this regard, FGD sludge generally ranks poorly in comparison to limestone and sewage sludge.

2. Regulatory Considerations

Recent shifts in regulatory attitudes show a growing concern for groundwater protection from seepage or leachate from the disposal of wastes. Given the recent Resource Conservation and Recovery Act of 1976, existing laws are legally adequate to insure protection of the geologic environment from waste disposal. However, because of the technical difficulties of completely characterizing an underground environment and of locating monitoring wells, regulation should rely on guidelines for site selection and waste acceptance and should allow for case-by-case assessment by professional geologists and geochemists.

Specific conclusions are as follows:

- The lead authorities for FGD sludge disposal appear to be the federal and state environmental protection agencies.
- The lead legislation is expected to be the Resource Conservation and Recovery Act of 1976, involving state resolution of Federally approved programs and the existing planning infrastructure established for 208 areawide wastewater management planning under the Federal Water Pollution Control Act Amendment of 1972.
- The combination of federal and state legislation is legally adequate to protect the environment during and after FGD sludge disposal; however, regulations are needed with site selection and waste acceptance guidelines based upon the characteristics of FGD sludge and research on potential environmental impacts.
- Additional legislation and standards may be required to protect worker health and safety. Administration of the health and safety requirements need clarification, especially between authorities of OSHA and MESA.
- Because of the non-point source nature of air and water emissions from FGD sludge disposal and the large variations in FGD sludge character, disposal should be regulated on a case-by-case basis.

3. Need for Additional Research and Information

The following research needs are believed most important at this time.

- Development of additional, more comprehensive physical and engineering properties data base and corroboration (or comparison) of results with field data. Of particular interest are:
  - triaxial compression tests for shear strength of untreated sludges to determine the ability to support loadings while unconfined;
  - dynamic triaxial compression tests for untreated sludges to simulate resistance to shear under seismic cyclic loadings applicable to various regions of coal reserves;
  - consolidation tests for untreated and soil-like treated sludges to simulate density and permeability under various static loadings related to overburden pressures; and
  - Atterberg limits for untreated sludges.

  Some of this testing is now underway in programs funded by EPA and other governmental agencies, and will be reviewed as available as a part of the Phase II effort.
- Development of a data base on key chemical impact issues relating to mine disposal. Of particular importance are:
  - the potential for TDS leaching from sludges and rates of TDS oxidation;
  - the potential for chemical attack of cement/concrete by sludge liquors and leachate;
  - the potential for SO_2 evolution during the initial stages of sludge disposal in underground mines with acidic environments;
  - the short-term effects of climate (e.g., freezing, excessive rainfall, etc.) on the physical properties of untreated sludges and pollutant mobility.

GLOSSARY

acid -- A substance containing hydrogen which may be replaced by metals with the formation of salts.

acre-foot -- A unit for measuring the volume of water, is equal to the quantity required to cover 1 acre to a depth of 1 foot and is equal to 43,560 cubic feet. The term is commonly used in measuring volumes of water used or stored.

alkaline -- Having the qualities of a base.

alluvial -- Describes earth materials that have recently (geologic time scale) been deposited by moving water.

aquiclude -- stratum that does not transmit groundwater and has no storage capacity.

aquifer -- A formation, or a group of formations, that is water-bearing and water-transmitting.

Atterberg Limits -- Indicate the boundaries as a soil proceeds from a solid to liquid state, including shrinkage limit, plastic limit, and liquid limit.

borehole -- A hole made with a drill, auger, or other tools.

bulkhead -- A construction for containment of a gas, liquid, or solid within a section of a mine.

confined aquifers -- Formations bound above and below by aquicludes, which transport groundwater under pressure.

Darcy's Law -- Relation of flow between hydraulic gradient and velocity applicable to laminar groundwater flow within a porous medium: $V = Ki$, where V = velocity, K = coefficient of permeability, and i = hydraulic gradient.

dip -- The angle at which a bed, stratum, or vein is inclined from the horizontal.

dragline -- A type of excavating equipment which casts a rope-hung bucket a considerable distance, collects the dug material by pulling the bucket toward itself on the ground with a second rope, elevates the bucket, and dumps the material on a spoil bank, in a hopper, or on a pile.

evapotranspiration -- Water withdrawn from land area by evaporation from water surfaces and moist soil and plant transpiration.

highwall -- The exposed vertical or near vertical wall associated with strip or area surface mines.

liquefaction -- Deformation due to buildup of high porewater pressures created by either cyclic or static stress applications.

outcrop -- The part of a rock formation that appears at the surface of the ground. It includes those deposits that are so near to the surface as to be found easily by digging.

overburden -- Material of any nature, consolidated or unconsolidated, that overlies a deposit of useful materials, ores, or coal.

precipitation -- The discharge of water, in liquid or solid state, out of the atmosphere, generally upon a land or water surface. The term precipitation is also commonly used to designate the quantity of water that is precipitated, measured in inches of depth, and includes rainfall, snow, hail, and sleet.

pyrite -- Iron disulfide, FeS_2; contains 46.7% iron, 53.3% sulfur.

relative density -- $D_r = \dfrac{e_{max} - e}{e_{max} - e_{min}} \times 100\%$

where e = in-place void ratio

e_{min} = void ratio of soil in densest state

e_{max} = void ratio of soil in loosest state

room and pillar -- A system of mining in which the coal or ore is mined in rooms separated by narrow ribs or pillars.

runoff -- The part of the precipitation that appears in surface streams. It is the same as stream flow unaffected by artificial diversions, storage, or other works of man in or on the stream channels.

strike -- The direction or bearing of a horizontal line in the plane of an inclined stratum that is perpendicular to the direction of the dip.

subsidence -- The lowering of the strata, including the surface, due to underground excavations.

tailings -- Mineral refuse from a milling operation usually deposited from a water medium.

unconfined aquifers -- Formations that allow groundwater to flow freely and seek its own level, with hydraulic gradients equal to the free surface anu invariant with depth.

water table -- The upper surface of the zone of saturation.

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33. Procedures Manual for Monitoring Solid Waste Disposal Sites, Wehran Engineering Corp. (Middletown, New York) and Geraghty and Miller, Inc. (Port Washington, New York), OSWMP, US EPA, Contract No. 68-01-3210, 1976. Draft report.

VI. OCEAN DISPOSAL

A. DESCRIPTION OF OCEAN ENVIRONMENT

1. Continental Shelf Environment

a. Physical Characterization

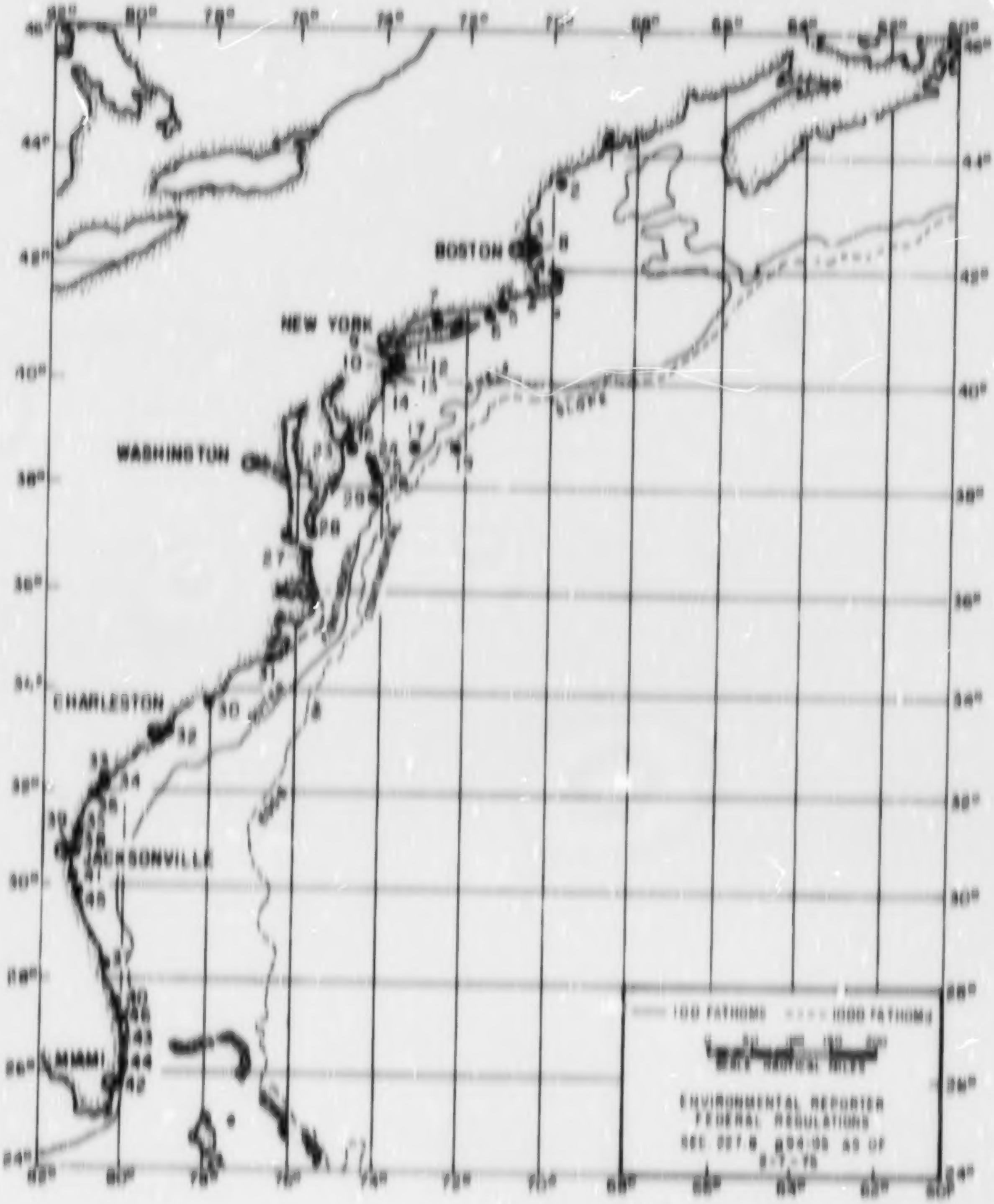
Figure VI-1 shows East and Gulf coastal waters, and the relationship of the coastline to the shelf break and lower limit of the continental slope.

The continental shelf extends from the shore to the shelf break which is generally defined by the 200-meter or 100-fathom contour. It is relatively broad off the Atlantic and the Gulf Coasts (approximately 60 miles wide off the New York and New Jersey coasts where most of the ocean dumping has taken place). It is characterized by topography of low relief, and because of its relatively shallow depth, sediments on the shelf are within the range of influence of storm waves and currents.

Currents on the shelf generally have identifiable to strong tidal components superimposed on mean current parallel to the shore. The mean drift may oscillate under influence of the wind. Recent studies by Lavelle, et al.(1) have shown that sediments in 20 meters of water can be quite readily transported by winter currents on the shelf. Within two weeks of injection at a point, radioactive sand could be traced a distance of 200 meters from the injection site. Within six weeks the radioactive pattern extended approximately 1500 meters.

Water characteristics over the shelf generally reflect the waters' proximity to land. Effects of rivers with their dose of sediments and nutrients (and very often contaminants as well) are observed in the water properties. In the vicinity of river discharges the waters are less saline than in the open ocean.

The oceanographic environment of the shelf can be characterized as one where physical processes are active. It is a border area between the land and the sea, and continuously changes under the influences of physical forces. Materials introduced into this environment will be subject to active physical attack. Although they may become seasonally stratified, the shelf waters are subject to extensive mixing due to natural tidal and wind-driven forces.


BOSTON
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FEDERAL REGULATIONS
SLOPE
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80°
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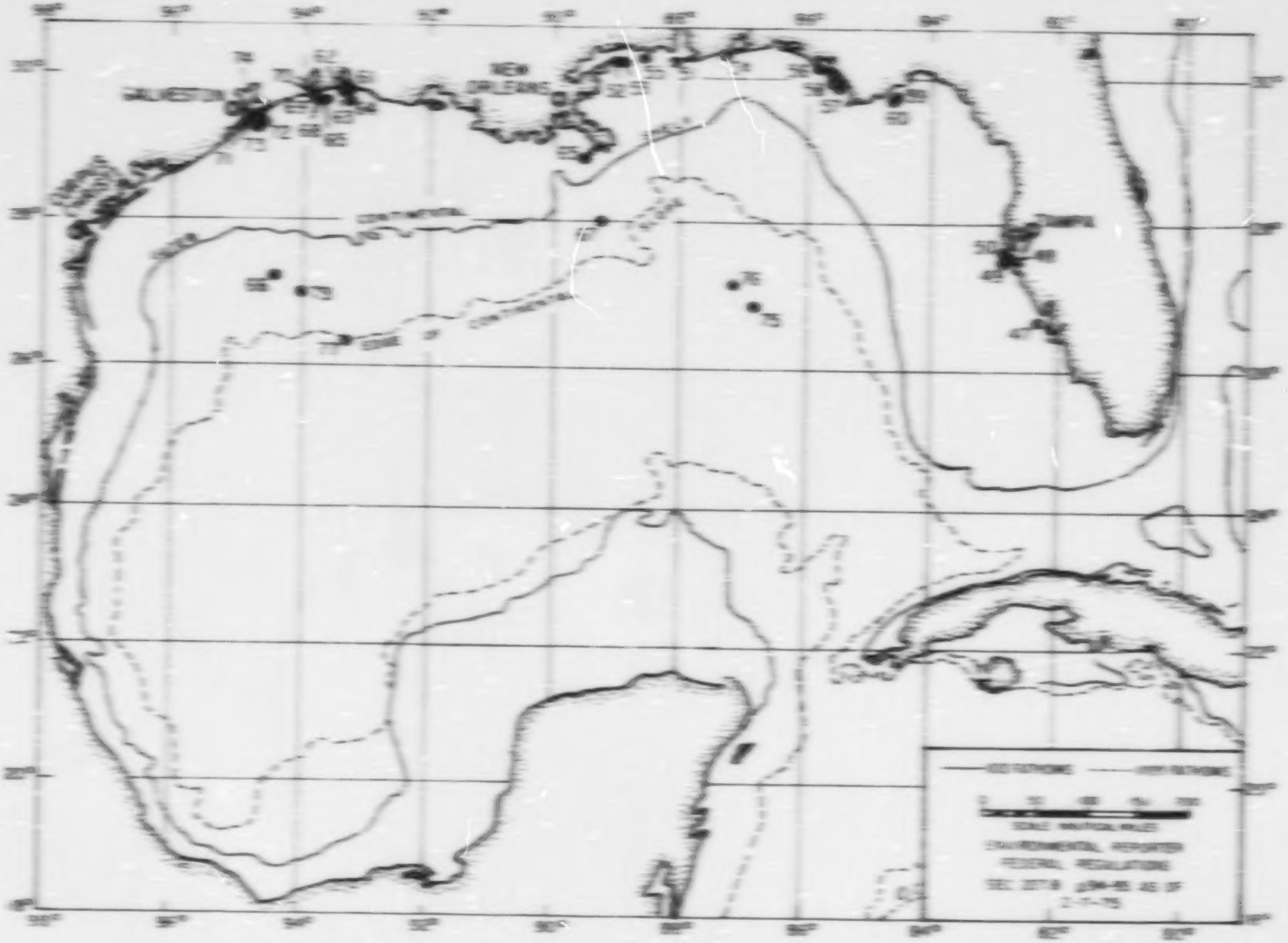
76°
74°
72°
70°
68°
66°
64°
62°
60°

FIGURE VI – 1A. ATLANTIC COASTAL WATERS AND DUMP SITES.


GALVESTON
NEW ORLEANS
TAMPA
CONTINENTAL
EDGE OF CONTINENTAL
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88°
86°
84°
82°
80°

FIGURE VI – 18. GULF COASTAL WATERS AND DUMP SITES.

b. Ocean Chemistry

The major constituents of seawater are relatively uniform and well known. Some of them, notably calcium and sulfate, can also be important constituents of FGD sludge. Table VI-1 lists seawater constituents reported to be present in excess of 100 mg/liter.

TABLE VI-1

MAJOR CONSTITUENTS OF SEAWATER

Constituent	Concentration mg/l		Concentration moles/l
Chloride	18,980		0.548
Sodium	10,561		0.470
Magnesium	1,272		0.054
Sulfate	884	(as S)	0.028
Calcium	400		0.0102
Potassium	380		0.0100

Source: Reference (2).

Considerably less definitive information is available concerning typical concentrations of trace elements in seawater. In particular, it appears that considerable variation exists in the results of different analytical efforts to detect heavy metals in seawater. One of the more recent reviews of the subject concluded, "It is clear that we need to know much more about concentrations, distributions, speciation, and toxicity of these elements before final conclusions can be reached about the hazards they represent to the marine ecosystem" (3).

Table VI-2 lists toxic heavy meatals of importance in marine pollution based upon their seawater concentrations and concentrations considered by the National Academy of Sciences (NAS) (4) to pose minimal risk of deleterious effects.

TABLE VI-2

TOXIC HEAVY METALS OF IMPORTANCE IN MARINE POLLUTION BASED ON THEIR SEAWATER CONCENTRATION AND TOXICITY

Element	Seawater Concentration (ug/liter)		Toxicity (ug/liter)	Ratios	
	A	B	C	A/C	B/C
Mercury	0.2[a]	0.05[a]	0.1	2	0.5
Cadmium	0.1	0.05	0.2	0.5	0.25
Silver	0.3[a]	0.1	1	0.3	0.1
Nickel	7[a]	2	2	3.5	1
Selenium	0.09[a]	0.45	5	0.018	0.09
Lead	0.03[a]	0.03[a]	10	0.003	0.003
Copper	3[a]	3[a]	10	0.3	0.3
Chromium	0.5	0.6[a]	10	0.05	0.06
Arsenic	2.6	2.3	10	0.26	0.23
Zinc	10[a]	5	20	0.5	0.25
Manganese	2[a]	2[a]	20	0.1	0.1

A: (5)
B: (6)
C: Water quality criteria: concentration considered to pose minimal risk of deleterious effect (4).

[a] Variations occur; some not related to salinity, depth, or ocean basin.

Source: Reference (3).

Four elements which emerge from such considerations as being of high potential hazard are mercury, cadmium, nickel, and zinc. The impact potential of these and other trace metals in the quantities found in FOD sludges are discussed below.

Trace element levels in unpolluted marine sediments are highly variable and ranges covering factors greater than 10X appear to be the rule rather than the exception. These levels are probably somewhat more reliably known than the corresponding values for seawater. In all cases, the range of concentrations extends above the levels reported for seawater.

c. Biological Regimes

The dominant aspect of the continental shelf ecosystem is the high degree of interrelationship therein. Shelf organisms frequently range between the upper layers of the water column (i.e., pelagic environments) and the bottom (benthic areas). Bluefish and mackerel are examples of such wide-ranging feeders of commercial and recreational importance. The continental shelf and associated estuaries constitute the majority of critical habitat for organisms valued by man. With few exceptions (e.g., pelagic fisheries for tuna and some deep dragging for lobsters) commercial fisheries' harvests are conducted on the shelf. The constant interaction among both biotic and abiotic aspects of the shelf ecosystems, and the importance of these ecosystems to man imply that emphasis be placed upon the impact potentials of FGD sludge disposal in continental shelf waters.

d. Effects of Ocean Dumping Activities on the Continental Shelf

The areas used most extensively for ocean dumping on the continental shelf (e.g., the New York Bight dump sites in Environmental Protection Agency (EPA) Region II) exhibit conditions representative of significant deterioration and/or radical alteration from uncontaminated areas. However, the location of such dump sites in the immediate area of influence of major independent sources of contamination, such as the Hudson River estuary in the New York Bight, makes discrimination of ocean dumping effects extremely difficult. There are exceptions. For example, the dumping of large volumes of dredged material in the New York Bight over the last 30 years has caused an elevation in bottom contours near the dump site of about 30 feet. Recently, EPA administrative hearings on the future of ocean dumping of Philadelphia's municipal sewage sludge concluded that short-term (about six months) utilization of a new dump site off the Delaware Bay produced a discernible and unacceptable pattern of increased heavy metal uptake and concentration in area biota, especially shellfish. The resultant decision was to continue the implementation of a near-term phase-out of the city's dumping activity. Recent studies in the New York Bight have also indicated that there appears to be rather rapid flux of introduced trace contaminants from the dumped material into the surrounding environment. Table VI-3 lists approved interim ocean dumping sites as of February 1975 (shown in Figure VI-1), and indicates their principal use. Most of these sites are for dredged materials, for which regulatory responsibility is shared between the Corps of Engineers and EPA. This list is subject to revision.

Figure VI-2 shows the pathways of ecological interaction in a simplified continental shelf ocean dumping scenario. It is intended as a reference point for the text discussions of potential impacts in subsequent sections of the report. As illustrated in Figure VI-2, the extensive interface between ocean organisms and man becomes a major factor in ocean dumping considerations.

2. Deep Ocean Environment

a. Physical Characterization

Deep ocean in this context means beyond the shelf break. Typically, it would refer to an area either part way down the continental slope or well beyond. The important differences as compared to the shelf are that it is a greater distance from land and is deeper. The greater distance from land is reflected in water properties which often do not receive the land's influence as directly as the shelf waters. The water off the shelf is more likely to be directly influenced by major ocean circulation features such as the Gulf Stream. The greater depth serves to isolate the bottom from wave forces and contributes to a more quiescent bottom environment in which sediments are less mobile than on the shelf.

The greater distance from land also has economic ramifications when transportation systems for sludge disposal operations are considered.

b. Deep Ocean Chemistry

There is some evidence that the deep ocean, particularly off the Atlantic and Gulf Coast shelves serves as a relatively stable sink for deposition of various materials. Systematic trends in trace element concentrations are evident, with concentrations of such elements in deep sea clays ranging from 2 to 12 times higher than in near-shore sediments (7). A principal difference between the deep ocean and shelf environments from a chemical standpoint is that the relative stability

TABLE VI-3

APPROVED INTERIM OCEAN DUMPING SITES, EAST AND GULF COASTS

NUMBER ON MAP (Fig. VI-1)	DEPTH (feet)	PRIMARY USE	NUMBER ON MAP (Fig. VI-1)	DEPTH (feet)	PRIMARY USE
	EPA REGION I		36	29-36	Sand with some Shell and Silt
1	120	Dredged Materials	37	31	Sand and Silt
2	180	" "	38	37	Sand, Shell, and Mud
3	186	" "	39	33	" " "
4	174	" "	40	39	" " "
5	180	" "	41	31	Sand and Shell
6	126	" "	42	41-48	" "
7	60	" "	43	26-57	" "
8	312	Toxic Waste	44	34	" "
	EPA REGION II		45	36	Fine Sand
9	60	Mud	46	11	Sand and Shell
10	105	Cellar Dirt	47	20	Silty Sand and Shell
11	90	Sewage Sludge	48	20	Poorly Graded Sand and Silt
12	38	Waste Acid	49	31	" " "
13	200	Wreck Dumping	50	24	" " "
14	23	Sand (Hopper Dredge)	51	44-48	Dredged Materials (Hopper Dredge)
15	20	" "	52	23-32	" "
16	18	" "	53	23-32	" "
17	6,370	Toxic Chemical Waste	54	36-42	" "
18	6,200	Chemical Waste	55	33-40	" "
19	6,300	" "	56	40	" "
20	–	Dredged Materials	57		" "
21	–	" "	58		" "
22	6,000	Conventional Munitions	59	36-42	" "
	EPA REGION III		60	36-42	" "
23	42	Sewage Sludge		EPA REGION IV	
24	120	Neutralized Acid Wastes	61	6+	Dredged Materials
25	130	Industrial Salt Waste	62	9+	" "
26	6,300	Arsenic Solutions	63	20+	" "
27	78	Sand	64	20+	" "
28	61	Silt and Sand	65	40+	" "
29	6,000	Conventional Munitions	66	2,460	Chemical Wastes
	EPA REGION IV		67	2,400+	" "
30	45	Sand and Silt (Hopper Dredge)	68	24	Dredged Materials
31	50	" " "	69	30	" "
32	28	Muddy Sand and Shell	70	6	" "
33	75	" "	71	36	" "
34	21	" "	72	30	" "
35	29-36	Sand with some Shell and Silt	73	30	" "
			74	12	" "
			75	Unspecified	Unspecified
			76	"	"
			77	"	"
			78	"	"

Source: Environmental Reporter, Federal Regulations Sec. 227.8, pp. 94-95, February, 1973.

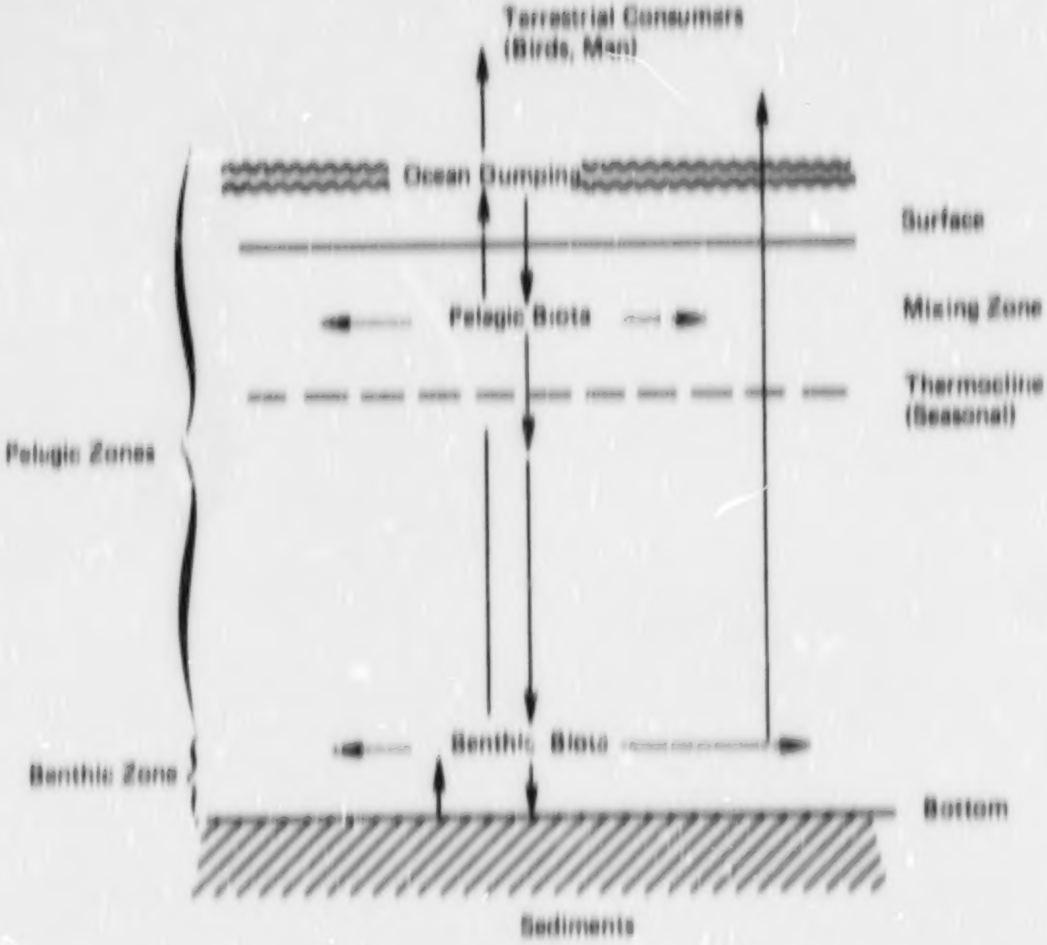

Terrestrial Consumers
(Birds, Man)
Ocean Dumping
Surface
Pelagic Biota
Mixing Zone
Thermocline
(Seasonal)
Pelagic Zones
Benthic Biota
Benthic Zone
Bottom
Sediments

FIGURE VI–2 PATHWAYS OF INTERACTIONS IN A SIMPLIFIED OCEAN DUMPING SCENARIO

of the deep ocean affords little opportunity for materials accumulated in the deep ocean to be made available to shelf environments.

c. Deep Ocean Biological Regime

The relative physical stability of the deep ocean is reflected in corresponding stability of deep ocean benthic communities. In general, far less is known about the ecosystem dynamics of such communities than their equivalents on the shelf. It appears that deep ocean benthic systems are less productive than shelf communities in terms of biomass, but far more stable and diverse. Community turnover time, that is, the time required for a stable community to evolve, is seasonal and perhaps involves a few years on the shelf. Corresponding values are unknown for the deep ocean, but estimates on the order of 30 years or more have been reported. Likewise, the sensitivity of the deep ocean communities to various types of stress is relatively unknown. It is believed that significant ecological stress is typically absent from the deep ocean benthos.

In contrast, it is important to remember that the upper layers of the deep ocean water column, particularly around the shelf margins, experience variations similar to those of on-shelf waters. In fact, because of exchanges of water mass in such areas and the mobility of many planktonic (free-floating) and nektonic (free-swimming) organisms, it is not appropriate to separate the pelagic communities of the upper and middle levels of the water column in the deep ocean and shelf environments. There is, however, reason to believe that events in the deep ocean benthos have little opportunity to influence continental shelf ecosystems in the western Atlantic and Gulf of Mexico, where up-wellings are not a major characteristic of the environment.

d. Effects of Previous Deep Ocean Dumping Activities

The deep ocean dumping off the Atlantic and Gulf Coasts has been confined to materials largely unrelated to FGD sludges, making analogies difficult. Off-shelf dump sites have been used for disposal of potentially toxic solutions from industrial waste streams. Comprehensive monitoring has not been performed; and deep ocean benthic communities have experienced limited exposure potential to date.

3. Introduction to Disposal Options

This assessment emphasizes ocean dumping from vessels as opposed to outfalls. Outfalls are not considered in depth for several reasons. First, it is believed that gross ecological impact potentials (i.e., suspended sediment concentrations) would pose a significant obstacle to outfall disposal in near-shore waters. Second, the construction of outfalls to extend over the shelf margin is believed economically infeasible on the Atlantic and Gulf Coasts. Finally, the regulatory situation concerning outfalls is in a state of flux.

The "baseline" ocean dumping scenario chosen for analysis involves the use of conventional bottom dump barges on the continental shelf. This would be the quickest, cheapest, preferred method in the absence of regulatory constraints. Thus, impacts are discussed below in terms of this mode of operation. Subsequent discussion focuses on major alternatives to this mode, including:

- dispersed dumping on the continental shelf;
- conventional dumping off the continental shelf (deep ocean);
- dispersed dumping off the continental shelf; and
- concentrated dumping of treated sludges on the continental shelf.

B. DESCRIPTION OF THE REGULATORY ENVIRONMENT

1. Statutory Base

The Marine Protection Research and Sanctuaries Act of 1972 (PL92-532) is the basis for all domestic regulation of ocean dumping. Several major provisions of this legislation are discussed below.

Policy

Section 2(b) of the Act states,

> "The Congress declares that it is the policy of the United States to regulate the dumping of all types of materials into ocean waters and to prevent or strictly limit the dumping into ocean waters of any material that would adversely affect human health, welfare, or amenities, or the marine environment, ecological systems, or economic potentialities."

Mandatory Considerations in the Issuance of Permits

The Act states that no dumping may take place without a permit from the Administrator of the EPA. Section 102(a) conditions the issuance of such permits upon determination by the Administrator that, "... such dumping will not unreasonably degrade or endanger human health, welfare, or amenities, or the marine environment, ecological systems, or economic potentialities." The specific review criteria to be used in reaching these determinations are prescribed as follows:

"(A) The need for the proposed dumping.

(B) The effect of such dumping on human health and welfare, including economic, aesthetic, and recreational values.

(C) The effect of such dumping on fisheries resources, plankton, fish, shellfish, wildlife, shore lines and beaches.

(D) The effect of such dumping on marine ecosystems, particularly with respect to –

(i) the transfer, concentration, and dispersion of such material and its byproducts through biological, physical and chemical processes,

(ii) potential changes in marine ecosystem diversity, productivity, and stability, and

(iii) species and community population dynamics.

(E) The persistence and permanence of the effects of the dumping.

(F) The effect of dumping particular volumes and concentrations of such materials.

(G) Appropriate locations and methods of disposal or recycling, including land-based alternatives and the probable impact of requiring use of such alternative locations or methods upon considerations affecting the public interest.

(H) The effect on alternate uses of oceans, such as scientific study, fishing, and other living resource exploitation, and nonliving resource exploitation.

(I) In designating recommended sites, the Administrator shall utilize wherever feasible locations beyond the edge of the Continental Shelf."

Penalties

Section 105 of the Act provides for civil penalties of up to $50,000 for each violation of the Act. It further provides for criminal penalties of not more than one year imprisonment, $50,000 fine, or both. Both the Government and private citizens are provided the opportunity to obtain injunctive relief by Section 105 of the Act.

Preemption of Other Jurisdictions

Section 106(d) of the Act precludes state, interstate, or regional authorities from adopting or enforcing any rules or regulations relating to ocean dumping. States may propose ocean dumping criteria to the EPA Administrator who may adopt them if he wishes. Thus, unlike the regulatory climate surrounding mine disposal alternatives, ocean disposal of FGD sludges by barge is the direct responsibility of only one agency, the Federal EPA.

Establishment of Regulations

Section 108 of the Act gives the Administrator the authority to establish such regulations as he deems appropriate. The existing and possible future regulations are discussed below.

2. Administrative Regulations

Ocean dumping regulations were first promulgated by the EPA Administrator in October of 1973 to become 40CFR 220-227. Subsequent amendments were adopted during 1974. On June 28, 1976 proposed revisions to the existing regulations were published in the Federal Register. A number of substantial changes are included in this proposal, and the existing regulations are discussed below in light of the changes proposed on June 28.

In general, Sections 220 through 226 of the regulations prescribe permit procedures to be followed by applicants and regional administrators. Adjudicatory hearing and enforcement procedures are also discussed. The sections of most concern with respect to potential ocean dumping of FGD sludges are parts 227 and pending part 228, which focus on criteria for the evaluation of permit applications and monitoring requirements. Relevant highlights of parts 227 and 228 are discussed below.

a. Consideration of Alternatives

The current ocean dumping regulations provide for consideration of a wide variety of alternative disposal options. The proposed regulations appear likely to go a major step further, to the extent of precluding ocean dumping in favor of any feasible alternative. The following factors will probably be included in determinations of the need for ocean dumping versus available options:

- degree of available treatment of the waste;
- available raw material and process changes;
- relative environmental impact and cost of ocean dumping and other alternatives, including but not limited to landfill, well injection, recycling, additional treatment, and storage; and
- irreversible or irretrievable consequences of the use of alternatives to ocean disposal.

Determinations of the cost feasibility of available alternatives to ocean disposal would not require that costs be competitive and would take into account environmental benefits as well.

b. Prohibited Materials

Under the existing regulations, absolute limits have been set concerning permissible levels in ocean-dumped wastes for mercury and cadmium, two constituents of importance in many FGD sludges. Existing mercury limits are 1.5 ppm in the liquid phase of a waste and 0.75 ppm in the solid phase. Based on available analyses, sludge liquors could be disposed of, but many of the sludges themselves would exceed this mercury limit. For cadmium, the existing limit on concentration in the liquid phase is 3.0 ppm, and 0.6 ppm in the solid phase. Again, eastern coal sludge liquors would appear to pass this test, but the range of cadmium in eastern FGD sludges (0.7 to 15 ppm) would in all cases exceed the existing EPA limit. Thus, unless these regulations are modified, eastern sludges could be precluded from ocean disposal entirely on the basis of the cadmium content of the solid phase.

Proposed revisions to the current regulations retain the existing limits for mercury and cadmium, but there are indications that these may change.

c. Other Factors Limiting Permissible Concentrations

In addition to the absolute limits on mercury and cadmium, FGD sludges would have to meet general criteria for dispersion under the existing regulations. This criteria requires that the concentration of material in the "mixing zone" (area swept out by the locus of points constantly 100 meters from the perimeter of the conveyance engaged in dumping, and 20 meters deep or less, depending upon the depth to the thermocline, halocline, or ocean floor) within four hours is not to exceed 0.01 of a concentration shown to be toxic to appropriate sensitive marine organisms.

In the proposed regulations, a "release zone" (100-meter locus as above, but no depth limit) is prescribed, but no formal "mixing zone." The existing toxicity limits (0.01 and 4 hours) are retained but apply to all of the marine environment subject to the influence of the dumped material. The following alternative techniques would be available to applicants for determining that area within which toxicity limits would apply:

- combination of field data and prediction by mathematical modeling;
- theoretical turbulent diffusion relationships, applied to known characteristics of the waste; and
- when no other means are feasible, it may be assumed that the waste is evenly distributed throughout the release zone to a depth of 20 meters.

This last option is effectively the same as use of the "mixing zone" defined in the present regulations. Overall, the proposed revisions would add considerable flexibility to this aspect of the permit review process.

d. Monitoring Requirements

Currently, in the absence of specific prescribed requirements the monitoring of various ocean dumping activities is developed somewhat *ad hoc* on a case-by-case basis. It is considered likely that a Section 228 will be added to the existing regulations, prescribing monitoring requirements in considerably more detail. These potential requirements are discussed below in the assessment of technology.

3. Agency Attitudes and Strategies

The following discussion is based on information and impressions gained from discussions with EPA personnel in The Office of Marine Protection and The Office of General Counsel in Washington; the EPA Environmental Research Laboratory in Narragansett, Rhode Island, EPA Region II; and the EPA Environmental Research Laboratories at Corvallis and Newport, Oregon. In general, the prevailing attitude towards ocean dumping is that it is a highly undesirable method of waste disposal. In some instances, this attitude is further reflected in a desire to phase out all ocean dumping activities. In all cases, regulators expressed a strong desire to utilise any available alternatives in preference to ocean dumping.

At the regional level there seems to be a general tendency to rely on the administrative means of control provided by ocean dumping regulations. Technical analyses as required are developed on a case-by-case basis. The burden of proof on technical matters clearly resides with prospective applicants for dumping permits. Agency inclinations toward reductions in ocean dumping have been boosted by a series of recent successes in efforts to phase out major dumping activities in Regions II and III. In Region II more than 25 industrial concerns previously disposing of waste at sea have found economically feasible landside alternatives and ceased ocean dumping. The EPA Administrator supported earlier agency recommendations to continue a tight phase-out of the ocean dumping of Philadelphia's municipal sewage sludge. This latter decision was characterised by agency personnel as a potential turning point. Some states, such as Maryland, have also taken action. In December 1975 the State of Maryland sued the EPA in an attempt to curtail the ocean dumping of raw sewage sludge by the City of Camden, New Jersey. In summary, the present trend is decidedly against the encouragement of ocean disposal.

In addition to the general trend towards phase-out of dumping, there has been a particular lack of encouragement to deep ocean disposal. In spite of the high priority given this type of disposal in the enabling legislation and regulations, the magnitude of deep ocean monitoring requirements, independent of other major cost factors, has indirectly discouraged potential deep ocean dumping permit applicants. Cost estimates for this type of monitoring activity range on the order of $1,000,000 per year per applicant.

C. FATE AND EFFECTS OF FGD SLUDGES ON THE CONTINENTAL SHELF

1. Disposal by Bottom-Dump Barge

As discussed in Chapter IV, work on sludge characterization has progressed to a point where the range of gross physical properties of the material (i.e., particle size distribution and density) has been determined. Some insight into the physical behavior of sludge after its introduction into a water environment has been gained, and areas where fruitful research could be accomplished have been identified. The major unanswered question which is critical to assessing the fate of sludges in the marine environment relates to their solubility in seawater.

If they are relatively insoluble, then there is the potential for considerably increasing the turbidity in a large region around the dump site. The small particle size assures that the material will stay in suspension for a long time if dispersed dumping takes place. The Massachusetts Institute of Technology (MIT) did related model studies on material in the vicinity of Boston outer harbor and Massachusetts Bay (8). The studies showed that suspended sediments with sinking rates similar to sludge would be transported for 45 miles or more. This may be typical of the distribution of sludge particles if dumped on the shelf and if they are relatively insoluble.

If FGD sludges are highly soluble in seawater, then dispersed dumping could lead to conditions where dissolution takes place before the particles reach the bottom, and any increase in ocean turbidity would be strictly temporary. Under these conditions the time frame of interest for assessing chemical and biological effects would be considerably shorter than for less soluble material.

a. Physical Transport

The effects of different transport processes on sludge disposal depend to a large extent on the form and properties of the material.

In the most generalized terms, material dumped into the ocean will go through one or more of the following phases: 1) convective descent, 2) collapse, and 3) long-term spreading. These phases are illustrated in Figure VI-3.

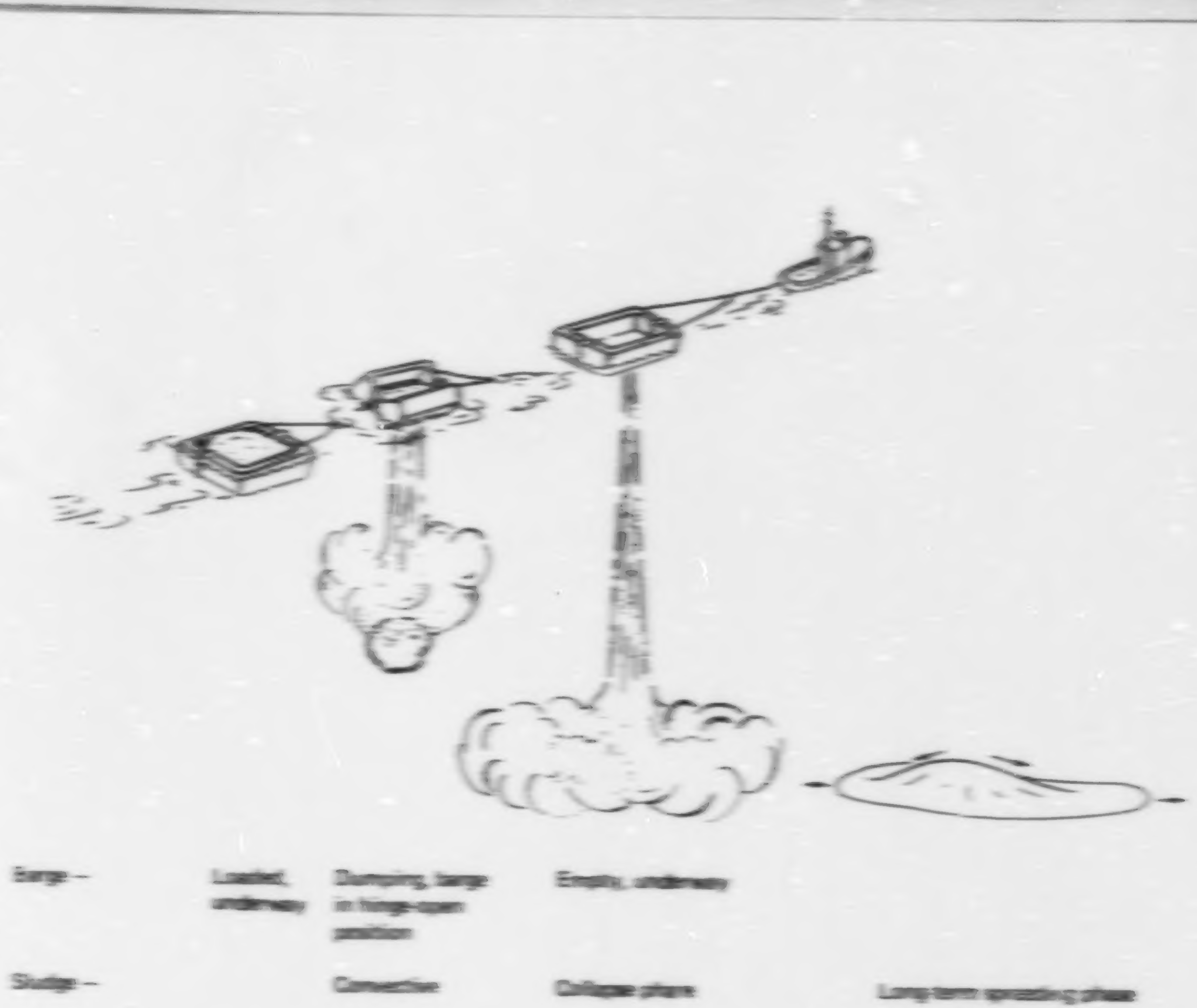

Barge --
Loaded, underway
Dumping, barge in hinge-open position
Empty, underway
Sludge --
Convection
Collapse phase
Long-term spreading phase

FIGURE VI–3 SCHEMATIC DIAGRAM SHOWING TRANSPORT PROCESSES — HINGED BOTTOM-DUMP BARGE

Convective descent is characterized by waste falling through the water under the influence of gravity and the momentum associated with its release. Initial mixing with and entrainment of ambient water occurs during the descent. This phase ends and the collapse phase begins either when the dumped material hits the bottom or reaches water of equal or greater density. At this point the waste material cloud collapses into a relatively thin layer (either on the bottom or at an intermediate depth), and the long-term spreading and redistribution forces of erosion and turbulent diffusion predominate.

If the material is solid, impermeable, and insoluble, the collapse and long-term spreading phases may be insignificant and the principal transport phenomenon will be rapid vertical descent. If the material is highly liquid and has a density near that of the receiving water, then all three phases may be significant in terms of physical transport.

Experiments using dredged material of various consistencies have demonstrated these phenomena and it is considered likely that a similarity in behavior will be noted between dredged material and FGD sludge. The following paragraphs further expand these concepts by focusing on three likely physical forms of the sludge.

Treated, Brick-Like Sludge

If the sludge is treated, resulting in a brick- or rock-like form, the sinking rate will be rapid and horizontal displacements from the release point due to ocean currents will be small, both during descent and after the material reaches the bottom. Water quality will be affected only to the extent that leaching of contaminants from the rock-like material takes place. Although the specific leaching rates of any material proposed for ocean disposal should be determined prior to the issuing of a dump permit, preliminary calculations based on available data indicate that leaching from rock-like fixed sludge in place on the ocean floor will not be environmentally significant. Dilution on the order of $1:10^{12}$ is indicated, assuming a bottom current of 15 cm/second, dilution into the bottom one meter of water, and a permeability of 10^{-6} cm/second.

Dewatered, Untreated Sludge

At some solids content (perhaps on the order of 50% for some materials) the material tends to hang together and fall through the water as a cohesive mass. Little quantitative information is available about this phenomena, but it is believed that under such conditions there is very little opportunity for release of included liquor from the main mass of sludge. As the body of waste falls through the water at relatively high speeds, some surface wasting occurs due to turbulent erosion. However, simple laboratory experiments and preliminary modeling results indicate that more than 95% of the dumped material would reach the bottom intact after rapid descent and remain as a heap on the bottom. Continuous utilization of the same site would result in the accumulation of significant amounts of dumped material. A heavily used mud dump site in New York Bight has measurably affected the bottom topography over an area of more than ten square nautical miles.

The FGD sludge which reaches the bottom would be subjected to the erosional forces of bottom currents at the depositional site. The grain size of the material in typical sludges is such that one might expect that unidirectional mean bottom current velocities in excess of 25 cm/second would be required to sustain erosion. However, oscillatory, rather than unidirectional currents prevail on the shelf, along with periodic wave distubances of large magnitude. All of these factors, combined with the apparent wide range of cohesiveness (and lack of cohesiveness) among different sludges, leave considerable uncertainty about the potential for sludge erosion and redistribution along the sea bed.

If 5% of the cohesive, untreated sludge is released into the water column as the main mass descends 200 meters to the bottom, then an initial (nearly instantaneous) volume dilution in the range of 1:500 to 1:2,500 is achieved for the released material. This material will be transported from the dump site by ambient currents.

Slurry-Dispersed Sludge

The important transport processes for diluted and dispersed sludge are turbulent mixing and the mean currents. Sludge which has been considerably diluted or which simply has a low solids content will very likely disperse widely and sink slowly.

Theoretical models exist for prediction of concentration versus time and space. However, the assumptions relative to the magnitude of dispersion coefficients used, and ambient density and velocity fields are critical. The range of initial dispersion which may be achieved covers several orders of magnitude. In general, if density stratification exists at the dump site, it is possible that sludge particles could be trapped above the thermocline and transported long distances before either dissolving or settling out.

Empirical data presented in Callaway, et al. (9) show that depth penetration of low density sewage sludge to the thermocline (11.5 meters) was achieved in less than 16 minutes after a quasi-instantaneous (6 minutes) release of 2,380 cubic meters from a stationary barge. The highest concentration after 16 minutes was observed at the surface and at a depth of 6 meters, and a dilution of 1:640 within 16 minutes was implied. If the barge had been moving at a typical 6 knots speed during the dump, it would have traveled 3,650 feet or some 15 barge lengths and would have increased both the turbulent mixing energy available and the volume of the receiving water above the thermocline. It is reasonable to assume that under such conditions a volume dilution of 1:9,600 would be achieved within 15 minutes. In the absence of a thermocline the depth of penetration would likely have been greater than observed.

FGD sludge differs from sewage sludge in two important respects. It is more dense than seawater and has a higher solids content. The higher density would tend to minimize the depth-limiting effect of any thermocline on mixing volume. If dispersion is desired in a bottom dump, special measures (e.g., stirring) may be required to assure particle suspension in the sludge because of its high solids content. Within very few minutes slurry-dispersed FGD sludge would be expected to be distributed throughout the available water column. This would of course add considerably to the mixing volume available in Callaway's case. An order of magnitude increase in the 15-minute dilution rate would be expected in waters 350-feet deep (i.e., 1:6,400 dilution for the stationary barge and 1:96,000 for the barge moving at 6 knots).

b. Environmental Impact Potential

Four principal categories of potential impacts for FGD sludge disposal in the ocean environment are discussed below. These are:

- impacts of benthic sedimentation;
- impacts of sludge suspended in the water column;
- impacts of sulfite-rich sludge; and
- trace contaminant impacts.

The chosen order of presentation does not necessarily reflect the relative significance of these several impact potentials.

Impacts of Benthic Sedimentation

In general, it is expected that disposal of FGD sludges on the continental shelf by bottom-dump barges would result in physical distribution of sludge in the benthic environment not unlike that experienced in conjunction with dredge spoil disposal. This would mean that the benthic environment in the vicinity of dump sites would be characterized by substrate substantially or entirely composed of sludge. Such conditions would have serious impact potential. Benthic ecologists generally regard the coarse-grained substrate (e.g., coarse sand) as most conducive to the establishment of rich, diverse marine benthic macrofaunal assemblages. Sediments of finer composition, especially if relatively uniform and uncompacted, provide the least stable and most limiting type of habitat (personal communication, Dr. Dale Calder, South Carolina Division of Marine Resources, 1975.) Field observations of a shallow bay which received an indeterminate amount of inadvertent overflow of FGD sludge tended to provide strong confirmation of the liability of sludge as a benthic substrate, although quantitative sampling was not initiated. It was apparent that the benthic macrofloral and macrofaunal communities in areas seemingly comprised largely of sludge were impoverished compared to otherwise similar control locations.

In areas of disposal of marine dredge materials the resultant benthic faunal assemblages have generally developed along recognizable patterns corresponding to sediment type. Where deposited dredged materials have been of a relatively fine, silty-clay nature and the ambient environment has been coarse sand, limited communities dominated by polychaete worms and certain pelecypod mollusks have become established on the dredge spoil areas. Different, often more diverse, communities exist on adjacent substrate. This type, and perhaps more severe limitations, would also be expected in FGD sludge disposal areas.

In addition to the physical character of the sludge, its relative lack of nutrient content may serve as a further limitation upon benthic faunal community establishment. The extent of this impact potential would be influenced by the availability of nutrients fluxed into the disposal site area from other sources, including estuarine detrital export and deposition from the upper portions of the overlying water column. Thus, although the lack of nutrients in sludge could prove to be a limiting factor, it is believed of secondary importance to the physical unsuitability of the material as a faunal substrate.

Impacts of Sludge Suspended in the Water Column

Elevated levels of suspended sediment have a number of well-documented effects on marine organisms under laboratory conditions. Considerable uncertainty is added to analysis of these impacts under field conditions because of the large variance in duration of organism exposure. In particular, it is extremely difficult to determine whether free-swimming nekton (such as finfish) would choose to avoid elevated concentrations of suspended sediment or would be attracted to such concentrations by the expected availability of food. The latter effect has been observed numerous times in the field, particularly among marine finfish. However, the observations related to suspension of natural benthic sediments which contain food organisms, rather than inorganic waste sediments dumped from a barge.

Receptor sensitivity is a second major variable. In general, the available information shows that relatively inactive species characteristic of the lower levels of the water column (such as flounders) have extraordinary resistance to lethal effects of suspended sediments. These species (as adults) compensate for potential clogging and mechanical damage to gills by such techniques as through-gut transport of sediments, and would in all likelihood survive the maximum levels of suspended sediment generated by ocean dumping (10).

Many of the dominant finfish of the continental shelf dump sites may be expected to exhibit intermediate sensitivity to suspended sediments. In quantitative terms this sensitivity may be defined as experiencing 10% mortality during 24-hour exposure to suspended sediment concentrations between 1,000 and 10,000 mg/liter. Such concentrations would be expected upon initial dilution throughout the dump site water column, but duration of organism exposure is expected to be brief in the upper and meso-pelagic zones. Species of importance in this category include striped bass (*Morone saxatilis*), croaker (*Micropogon undulatus*), bay anchovy (*Anchoa mitchelli*), and weakfish (*Cynoscion regalis*) (10).

In general, the free-swimming estuarine organisms most sensitive to suspended sediments are sub-adult or younger forms. It is reasonable to expect the same in marine waters. Forms which have been shown to experience 10% mortality during 24 hours exposure to sediment concentrations less than 900 mg/liter include juvenile bluefish (*Pomatomus saltatrix*) and adult silversides (*Menidia menidia*). Juvenile menhaden (*Brevoortia sp.*), a commercially valued species, falls somewhere between this and the preceding category in sensitivity (10).

In addition to the potential for mortality to commercially or recreationally valued organisms associated with prolonged exposure to elevated concentrations of suspended sediments, a variety of adverse sub-lethal impact potentials exist at these and lesser exposure values. Many of these sub-lethal effects may be classified as examples of reduced ecological efficiency. The hogchoker (*Trinectes maculatus*), a flounder seemingly insensitive to extended exposure to sediment concentrations in excess of 100,000 mg/liter, nevertheless was shown to expend significantly more energy at concentrations of 1,240 mg/liter than under control conditions (10). Eighty to ninety percent reductions in carbon uptake by low-salinity estuarine phytoplankton occurred over the course of one hour's exposure to suspended sediment concentrations between 1,000-2,250 mg/liter, and 100-150 mg/liter produced reductions on the order of 15-50% (10). *Acartia tonsa*, a calanoid copepod typical of seasonally dominant zooplankton of dump site areas, exhibited reductions in feeding efficiency (measured as carbon uptake) of 20-100% when exposed for short (5-10 minute) and somewhat longer (125-minute) periods to suspended sediment concentrations of

50-1,000 mg/liter. A somewhat nonselective feeder, this copepod apparently eats a lot of "junk" instead of its normal food when in the presence of elevated concentrations of suspended sediment (10).

A third major variable affecting the magnitude of suspended sediment impacts is the type of sediment involved. All available data indicates that the finer particles (in the silt/clay and finer range) have greater impact (than coarser particles) by each of the mechanisms discussed above (11). Untreated FGD sludge would be in this silt/clay range. The extent to which other contaminants (including sulfite and heavy metal residues) are part of the dumped sludge is another important aspect of impact potential. Through their use of such compensatory mechanisms as through-gut transport, fish and other organisms pass varying concentrations of suspended sediment into their digestive tracts. While the extent to which this occurs may vary with time of exposure, concentrations of previously suspended sediment in the stomachs of estuarine fishes in the range of 3,000 mg/liter have been recorded (10). Once within the stomach of a fish, particles are exposed to acidic conditions (pH of 1 or 2) capable of stripping adsorbed contaminants and making those contaminants available for damage or concentration within the organism or elsewhere in the food web (11). Thus, certain major contaminant impact potentials may be relatively independent of the extent to which water column concentrations of sulfite or trace metals might be increased by dumping activities. These types of impacts could be important over the long term at dump sites to such benthic finfish as cod and flounder, whose feeding habits involve sediment suspension and ingestion.

Impacts of Sulfite-Rich Sludge

The impact of the introduction of sulfite into the ocean environment as consequence of FGD sludge disposal is of interest for two reasons. First, sulfite has a measurable toxicity; and second, it will react with dissolved oxygen, leading to a depletion of dissolved oxygen (DO). Sulfite is present in FGD sludges both as soluble sulfite salts in the interstitial liquid and as solid calcium sulfite. Soluble sulfite concentrations in the interstitial liquid can range from about 4×10^{-2} M (about 3,000 ppm) in washed dual alkali filter cakes down to about 1×10^{-3} M (less than 100 ppm) in sludges from direct slurry scrubbing systems. If one were to dispose of FGD sludges in a manner that insured an instantaneous dilution by a factor of 10^4, the soluble sulfite component would be diluted to a concentration in the range of 4×10^{-5} to 1×10^{-7} M. At those concentrations there should be little or no impact from that component.

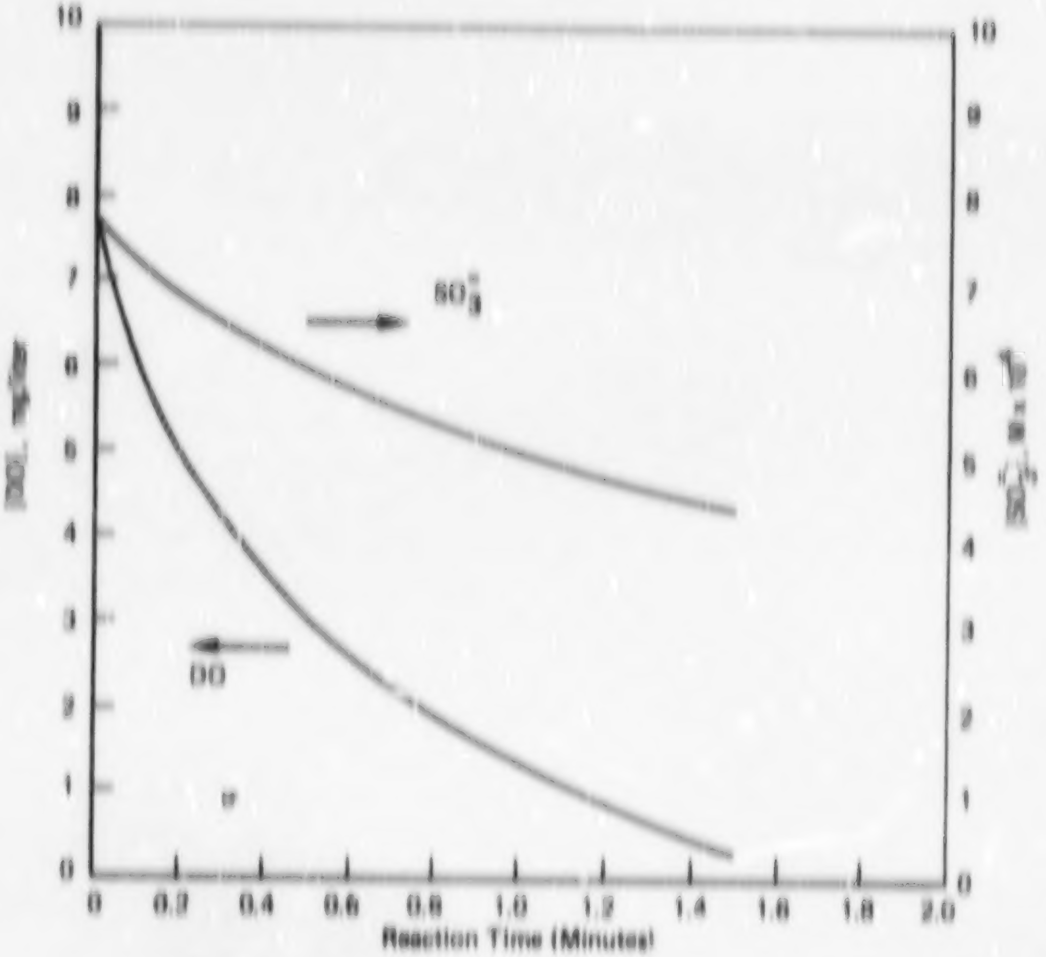
A more important consideration is the possible impact of sulfite present as the insoluble calcium salt. If one considers a one-liter sample of a typical FGD sludge containing 50 weight % solids, it will contain about 765 grams of solids. Assuming that all of the solid materials are $CaSO_3 \cdot 1/2\ H_2O$ (MW = 129.2), a liter of sludge will contain about 5.9 gram moles of sulfite as calcium sulfite. If the sludge is diluted by a factor of 500 in the course of being dumped, a total sulfite concentration of about 0.012 M will result. That concentration is in the range where there could be impacts from sulfite itself or from reductions in dissolved oxygen which would accompany any sulfite oxidation which occurred.

If it is further assumed that the uptake of sulfite-rich suspended particles by fish in the water column is about the same as observed using other sediments in laboratory studies, the resultant concentration of sulfite in the stomach of disposal area fish might be on the order of 0.006 M. This concentration is roughly six times the median 50% lethal concentration for fish at pH 6 (0.001 M) observed under laboratory conditions (11). Sulfite toxicity has been demonstrated to be pH dependent, increasing with decreasing pH. Thus, a concentration of 0.006 M sulfite in the stomach of finfish, where pH levels would be 1 or 2, may have serious impacts compared to those reported from previous studies at pH 6. However, more data needs to be obtained concerning organism uptake of suspended particles of FGD sludge during the short-term exposures that would be characteristic of ocean dumping conditions before the real impact potential of sulfite-rich sludges regarding toxicity can be accurately quantified.

The solubility of calcium sulfite depends on the ionic strength of the solution in which it is to be dissolved. Seawater has an ionic strength, μ, of about 0.7. At that ionic strength the apparent solubility product of $CaSO_3 \cdot 1/2\ H_2O$, "K_{sp}'," has been calculated to be about 8×10^{-6}. Since the apparent solubility product is equal to the product of the concentrations of calcium and sulfite in solution, a solution of seawater saturated in calcium sulfite should be about 8×10^{-4} M in sulfite (the calcium concentration in seawater is approximately 0.01 M). That concentration is about 50% greater than the total amount of sulfite which would actually be present if FGD sludge were diluted by a factor of 10^{4} upon disposal. Thus, in the absence of oxidation one would predict that at equilibrium all of the sludge would dissolve and a concentration of about 6×10^{-4} M sulfite would be present.

However, even at concentrations less than 10^{-3} M, sulfite will react rather rapidly with any dissolved oxygen in the solution (12). The oxidation of sulfite by dissolved oxygen is a very complicated chain reaction which is catalyzed both positively and negatively by other chemical species present in the solution--many catalysts are effective at parts per million levels. Cations like copper and cobalt accelerate the oxidation reaction, while organic substances tend to inhibit it. Thus, an accurate estimate of the rate at which sulfite would be oxidized by dissolved oxygen in seawater is difficult unless one conducts laboratory measurements utilizing actual samples of the seawater in question. However, Rand and Gale (13) have studied the uncatalyzed reaction at concentrations of sulfite and dissolved oxygen similar to those of interest here. They studied the depletion of dissolved oxygen from a solution which initially contained 7.7 mg/liter DO; dissolved oxygen levels in the upper water column in the ocean tend to be in the range of 7-10 mg/liter. Into that oxygenated solution they introduced sodium sulfite to produce an initial concentration of 9×10^{-4} M which is within a factor of two of the 6×10^{-4} M sulfite concentrations which would be present after a 10^{4} dilution of FGD sludge. The data from one typical run, illustrated in Figure VI-4, show the concentration of dissolved oxygen after slightly over one minute of reaction.

Thus, if the FGD sludge solids would dissolve instantaneously upon being diluted and dumped and if the oxidation in real seawater would proceed as rapidly as the above uncatalyzed experiment proceeded, one would expect to find severe reductions in dissolved oxygen in the vicinity of the dump. Oxygen depletion would probably be a more severe impact than



Source: Reference (12).

FIGURE VI-4 OBSERVED SULFITE OXIDATION RATES

the residual sulfite because, as the data above indicate, the total sulfite concentration was reduced by 4×10^{-4} M in conjunction with the reduction of DO from 7.7 mg/liter to 0.8 mg/liter. Thus, the 6×10^{-4} M sulfite concentration present in a volume of diluted FGD sludge should be reduced to approximately 1.5×10^{-4} M by oxidation.

The above discussion presupposes that the dissolution of FGD sludge solids is instantaneous. Calcium sulfite is very insoluble and it is unlikely that complete dissolution would occur in one or a few minutes. We are not aware of detailed studies of calcium dissolution rates at such low concentrations of calcium sulfite in seawater; however, we have made qualitative observations in the laboratory in which 10 mg of FGD sludge was suspended in 100 ml of 0.6 M NaCl. Only after 10 minutes of stirring was there a discernable decrease in the amount of suspended solids. More than 30 minutes was required for essentially complete dissolution. Thus, it is likely that solids dissolution rather than oxidation would be the limiting step in the dissolution/oxidation sequence. If dissolution is very slow, the impact that will need to be considered is that of the presence of about 6×10^{-4} M calcium sulfite in solid form and the accompanying impact of the presence of about 76 ppm of suspended solids which is equivalent to that concentration of solid calcium sulfite.

Trace Contaminant Impacts

As noted above, proposed EPA regulatory requirements could preclude the disposal of FGD sludges at sea based solely on the reported range of cadmium concentrations in the solid phase of sampled sludge. In spite of the prescribed limits on mercury and cadmium, a thorough investigation of the impact potentials of these and other sludge-related trace contaminants was conducted. The principal base for the discussion below comes from the extensive review and development of recommendations for water quality criteria adequate to safeguard all marine and estuarine aquatic life performed by a special team under the auspices of the NAS in 1972. The results of this effort were published by the EPA as part of its comprehensive recommendations for water quality criteria (4). However, these, too, are being revised. To supplement this information, a retrieval and analysis of recent scientific literature on selected contaminants (mercury, cadmium, and selenium) was undertaken. The results of this effort provided no basis for revising (either upward or downward) the minimum risk thresholds identified by the NAS team.

The problems created by trace contaminants in marine systems are extraordinarily complex. In addition to the traditional considerations of direct toxicity, potentials for biological accumulation and magnification of trace contaminants to levels hazardous to consumer organisms in the food web have been receiving increasing attention. Recent research has also uncovered an increasing body of knowledge on the complex series of synergistic and antagonistic relationships among the various trace contaminants, which can become controlling factors of toxicity. Perhaps the single greatest problem in evaluating the trace contaminant impacts potential of FGD sludge in the ocean is the lack of definitive empirical data concerning the short-term and ultimate availability of trace contaminants in the solid fraction of the material. In particular, critical information is lacking on sludge dissolution rates, ionic speciation, and typical uptake and concentration patterns of marine organisms exposed to both dissolved and solid fractions of sludge trace contaminants.

Liquid Phase Trace Contaminants. If, as anticipated, initial dilution by a factor of about 500 is achieved upon disposal at sea and the limited available data reflects "worst case" ranges of trace contaminants in sludge liquor, the resultant release of most trace contaminants into the marine environments from sludge liquor would be expected to pose minimal risk to marine life. Table VI-4 shows the range and median concentrations of twelve trace contaminants of interest in FGD sludge liquors derived from the burning of eastern coal, as compared to the criteria considered by NAS to pose minimal risk to the marine environment. It is important to note that the high values represent sludges containing fly ash believed to be a reservoir for heavy metals in sludge.

Based upon the concentrations reported in Table VI-4, the anticipated initial dilution of sludge liquor by a factor of 500 could result in concentrations of five trace metals approaching or in excess of the "minimum risk" levels recommended by NAS. In decreasing order of apparent impact potential, these metals are: mercury, zinc, selenium, cadmium, and nickel. Four of these five (excepting selenium) correspond to four of the five toxic elements of principal concern identified by Ketchum et al. (3).

TABLE VI-4

TRACE CONTAMINANT CONCENTRATIONS IN REPORTED SLUDGE LIQUORS FROM EASTERN COALS AND NAS MINIMAL RISK CRITERIA FOR THE MARINE ENVIRONMENT

	NAS Minimal Risk Criteria (ppm)	Median in Liquor[c] (ppm)	Range in Liquor[c] (ppm)
Antimony	0.2[a]	1.2	0.46-1.6
Arsenic	0.01	0.020	<0.004-1.8
Cadmium	0.0002	0.023	0.004-0.1
Chromium	0.01[b]	0.020	0.001-0.5
Copper	0.01	0.015	<0.002-0.4
Fluoride	0.50	3.2	1.4-70
Iron	0.05	0.026	0.02-0.1
Lead	0.01	0.12	0.002-0.55
Mercury	0.0001[a]	0.001	0.0009-0.07
Nickel	0.002	0.13	0.03-0.91
Selenium	0.005	0.11	<0.005-2.7
Zinc	0.02	0.046	0.01-27

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[a] Concentrations considered to pose hazard; minimal risk levels not recommended.

[b] Concentration recommended for oyster-producing areas.

[c] Results of 4 to 15 observations (see Table IV-3).

Source: Reference (4).

A 500-fold dilution of the maximum reported concentration of mercury in sludge liquor would result in a concentration of 0.0014 ppm. This would exceed the 0.0001 ppm threshold identified as a hazard to the marine environment. Mercury can be biologically concentrated several thousand times and has been implicated as a toxic agent in both acute and long-term pollution episodes.

The anticipated initial dilution of zinc would result in a water column concentration of 0.054 ppm, which would exceed the minimum risk threshold of 0.02 ppm. However, it would be below the hazard threshold of 0.1 ppm. Another potentially troublesome aspect of zinc levels in FOD sludge is the tendency of zinc to interact synergistically with cadmium and copper, thereby increasing the toxic potential of all three elements (4).

Initial dilution of the maximum reported concentration of selenium in FOD sludge would result in water column concentrations of 0.0054 ppm. This concentration would slightly exceed the minimum risk criteria of 0.005 ppm. Unlike zinc, selenium appears to have a tendency to act antagonistically with mercury and cadmium to reduce their toxicities. However, it also appears that the mechanism of interaction might be conducive to long-term retention of the otherwise toxic mercury and cadmium within an organism. This could create further opportunities for higher levels of food web contamination than might otherwise occur if traditional toxicity mechanisms were operative. In general, the impact potential of selenium in marine systems is poorly understood.

Initial dilution of the maximum reported concentrations of cadmium and nickel in sludge liquors would be expected to result in water column levels roughly equivalent to the NAS minimal risk criteria. The extent to which these concentrations might present a problem in the disposal area environment would in part depend upon the background concentrations of these and other elements which could react synergistically with the incrementally added waste. Such factors are highly variable and would need to be evaluated on a case-by-case basis. The resultant concentrations of the other seven trace contaminants considered in Table VI-4 would be expected to present minimal risk to the marine environment. The extent to which typical rather than worst case sludges would present differing risks in trace contaminant impact potential is discussed below in conjunction with control options.

Solid Phase Trace Contaminants. The reported range of trace contaminant levels in FGD sludge solids encompasses considerably higher concentrations than found in the sample sludge liquors. Table VI-5 shows these concentrations in comparison to the NAS recommended minimal risk criteria for nine trace elements in sludge solids. As in the case of sulfite, the impact potential of trace contaminants bound or adsorbed to solid fractions of the sludge will be dependent upon critical vaviables such as dissolution rate and particle uptake by free-swimming organisms. Too little is known of these types of interactions over the short-term to allow for a feasible prediction of quantitative impacts.

Trace Contaminants in Organically-Enriched Environments. A special set of impact potentials may be associated with the deposition of FGD sludges in organically-enriched enviroments, such as the sewage sludge and dredge spoil dump sites in the New York Bight. Recent evidence indicates that heavy metal contamination of the Bight and other dump sites is available to and being fluxed into local biotic populations. It is believed that the introduction of organic wastes in these areas provides a means of concentrating halogenated hydrocarbons (including pesticides) and heavy metals (as organic-metallic complexes) in lipid tissues of local organisms. While the heavy metal concentrations in FGD sludge are typically much less than those in the contaminated dredge spoil and sewer sludge, the overall effect of dumping these materials into a common area would be to increase the total amount of toxic metals available for complexing and incorporation into the food web. On the other hand, burying dredge spoil and sewer sludge with FGD sludge might dilute the amount of available metals in the surficial sediment in grossly contaminated areas. Overall, this strategy appears to have substantial liabilities and would require thorough investigation prior to implementation.

2. Environmental Impact of Applicable Control Options

a. Restricting Types of Sludge Disposed of on the Continental Shelf

Assuming that the sludge to be disposed of is untreated prior to disposal and therefore remains in the same consistency and particle size

TABLE VI-5

CONCENTRATIONS OF TRACE ELEMENTS IN SLUDGE SOLIDS AND "MINIMAL RISK CRITERIA"

	NAS Minimal Risk Criteria (ppm)	Median in Sludge[c] (ppm)	Range in Sludge[c] (ppm)
Arsenic	0.01	33	3.4-63
Cadmium	0.0002	4.0	0.7-350
Chromium	0.01[a]	16	3.5-36
Copper	0.01	14	1.5-47
Lead	0.01	14	1.0-55
Mercury	0.0001[b]	1	0.02-6.0
Nickel	0.002	17	6.7-27
Selenium	0.005	7	0.2-19
Zinc	0.02	57	9.0-118

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[a] Concentration recommended for oyster-producing areas.

[b] Concentration considered to pose hazard; minimal risk levels not recommended.

[c] Results of 5 to 9 observations (see Table IV-2).

Source: Reference (4).

range, the restriction of sludge type could significantly impact two of the four principal impact potentials discussed above. The impacts of benthic sedimentation, as discussed above, would not be affected to any significant degree by restricting types of untreated sludges disposed of on the continental shelf by bottom dump-barges. Likewise, the impacts of suspended sludge in the water column would not be affected from the gross standpoint of organisms' sensitivity to sediments in general. However, two subsets of the suspended sediment impacts, the impacts of sulfite and associated trace contaminants, could be significantly mitigated by restricting the types of sludges disposed of at sea. As noted above, the range of trace contaminant concentrations in sludges from eastern coals is such that in a few instances (i.e., where fly ash is present) even the lowest values in that range would still present disposal problems under existing EPA criteria. Likewise, preempting disposal of sulfite-rich sludges might foreclose ocean disposal as an option for a significant percentage of potential applicants in East Coast locations. Nonetheless, disposing of only sulfate-based sludges with trace contaminant concentrations at or below the median values thus far reported would substantially mitigate the sulfite and trace contaminant impact potentials discussed above.

b. Disposal by Dispersion

If FGD sludge slurries were pumped overboard in a manner sufficient to achieve instantaneous dilution on the order of 5,000 to 10,000, three of the four impact potentials discussed above would be substantially mitigated. The impacts of benthic sedimentation and of suspended sludge in the water column could be mitigated by dispersion. There would be a trade-off in trace contaminant impacts. Such contaminants would be given wider distribution by dispersion, but the local concentrations associated with dispersed disposal would bring all trace contaminant levels into the range of minimal risk criteria. Sulfite impacts would remain of potential significance in the dispersed disposal option. As noted above, the assumption of initial dilution on the order of 10^4 would still result in potential problems of sulfite oxygen demand. The potential toxicity of concentrations on the order of 0.00012 M is still substantial, since this is roughly equivalent to the reported median lethal concentration at pH 6.

c. Concentrated Bottom Disposal

For purposes of this discussion, concentrated bottom disposal is presumed to include chemical treatment of FGD sludge resulting in a cement- or brick-like waste product. It appears that all four of the principal impact potentials discussed above (sedimentation, suspension, sulfite, and trace contaminants) would be substantially mitigated by this control option. Not only would the problem of benthic sedimentation be avoided, but the presence of brick-like chunks on the ocean floor could serve as the basis for creation of attractive new marine benthic habitat. Of course, overriding this and all other considerations of this control option is the question of dissolution. If the lifetime of the material in concentrated form is relatively brief, two of the advantages of this option would be removed. The trace contaminants within the treated sludge would become available upon dissolution and still might be problematic. In fact, they might be more so over the long term with this option because of the lack of initial dilution. If dissolution also results in loss of structural integrity prior to total dissolution, the opportunity for some benthic sedimentation impacts may be present, dependent upon the frequency and strength of mechanisms of benthic disturbance, such as storm waves. Provided that questions concerning the dissolution of concentrated, treated sludge can be resolved, this option appears to offer considerable promise.

d. Chemical Treatment of Sludge

With the exception of the above mentioned option of concentrated disposal of brick-like treated material, chemical treatment appears to offer few, if any, advantages over the traditional bottom-dump disposal of untreated FGD sludge. The sulfite impacts discussed above might be mitigated to considerable degree by chemical treatment, but the impacts of benthic sedimentation and suspended sludge in the water column would be comparable to those associated with typical untreated material. Trace contaminant impact potential could be equal to or possibly greater with chemically-treated sludge than with untreated material. This is principally because it appears that trace contaminants may be added by certain treatment processes, such as through the addition of ash. In counterbalance the rate of availability of trace contaminants could be slowed somewhat by chemical treatment. Overall, chemical treatment, other than that which would result in a brick-like material, appears to offer little promise as an ocean disposal control option.

D. FATE AND EFFECT OF FGD SLUDGES IN THE DEEP OCEAN

1. Disposal by Bottom-Dump Barge

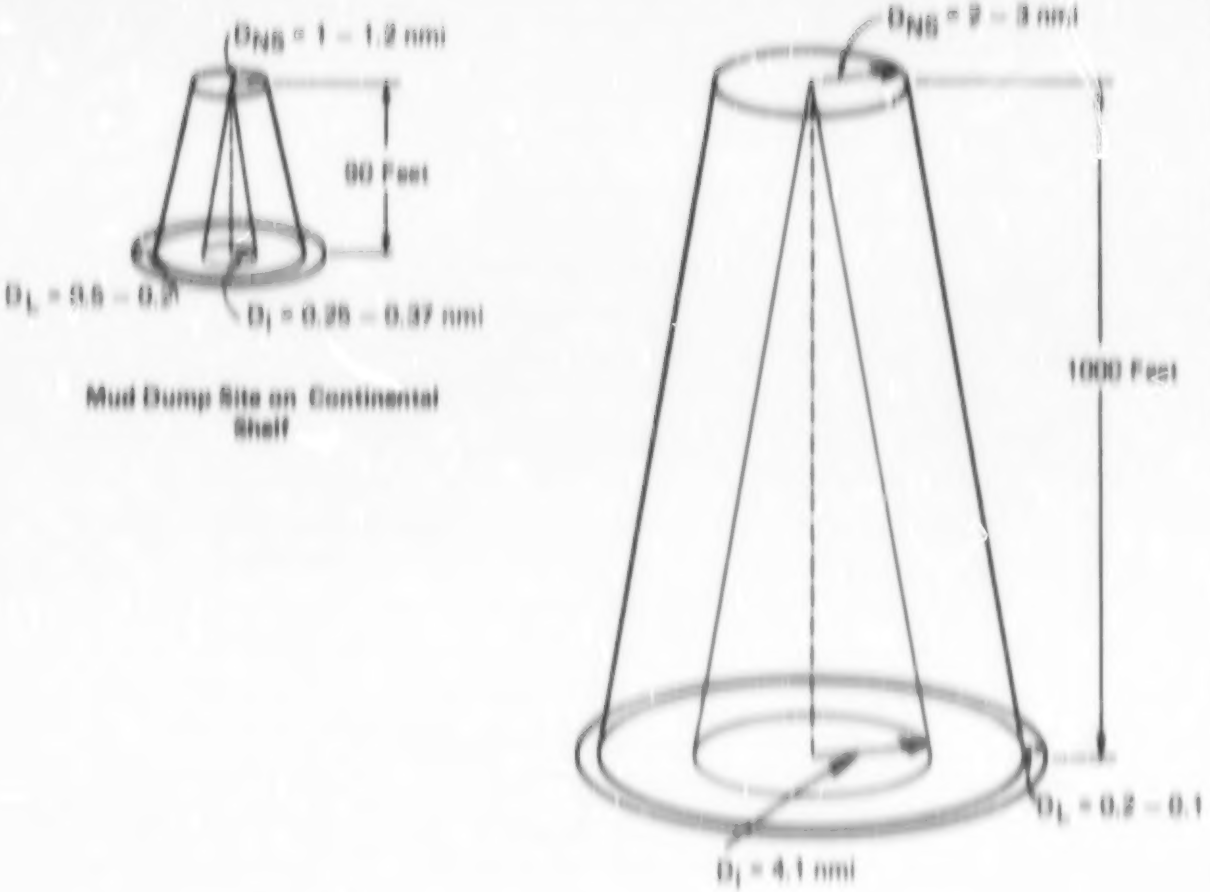
a. Physical Transport

The same principles of physical transport on the continental shelf apply to the deep ocean environment, with some modifications due to increased water depth. There are two main factors which differentiate these two segments of the ocean environment. One is the relative isolation and quiescence of the deeper parts of the ocean compared to the continental shelf. Storm effects which readily stir the continental shelf sediments may not be in evidence at all off the shelf.

The other factor relates to the greater distance dumped material falls through the water column. More water is available for dilution, and more time is available for dissolution. It is not known whether FGD sludge would dissolve before it reached the bottom in the deep ocean.

No off-shelf dump site has been used for disposal of sludge-like materials in circumstances that would permit measurement of material accumulation. Validated models which could predict sludge accumulation do not exist, and the models which do exist generally are data limited in that unverified estimates of many input parameters must be used to make the models function. In this situation it is useful to examine long-term shallow water (on-shelf) dump sites and to make reasonable extrapolation to deep water. In this way, at least some insight might be gained as to the area of the bottom which could be expected to experience sludge accumulation. (See Figure VI-5.)

The mud dump site in New York Bight has been studied by comparing present-day bathymetry with that existing prior to the period when dumping commenced. The water was originally 90 feet deep. In the 33 years since dumping started, sediments have accumulated to a maximum depth of 30 feet. In excess of five feet of mud has accumulated over an area 3.2 nautical miles (nmi) across. Isopach mapping indicates that the major accumulation has occurred within 1.8 nmi of the designated dump site (two square miles). It is likely that more than 10 square nautical miles of bottom have been


D_{NS} = 1 – 1.2 nmi
90 Feet
D_L = 0.5 – 0.2
D_I = 0.25 – 0.37 nmi
D_{NS} = 2 – 3 nmi
1000 Feet
D_L = 0.2 – 0.1
D_I = 4.1 nmi

Mud Dump Site on Continental Shelf

Hypothetical Site, Off-Shelf

Notation: D_I = Initial displacement during disposal process
D_{NS} = Displacement due to navigation errors and short dumps
D_L = Displacement due to long term bottom transport processes

FIGURE VI–5 FACTORS CONTRIBUTING TO THE CUMULATIVE DISTRIBUTION OF DUMPED SLUDGE

covered. Thus, cumulative distribution includes contributions from navigational errors, short dumps, transport processes, and dispersion during disposal and bottom transport after disposal, all averaged over the 33 years of dumping at the site.

Short dumps may be of two varieties, those due to heavy weather or emergency which may be located several miles from the dump site, and those due to over-anxiousness of the dump crew. Lumping navigation error and over-anxiousness, we estimate that 1-1.2 nmi of the 1.8 nmi distribution could be accounted for by short dumping.

Studies conducted by the National Oceanic and Atmospheric Administration (NOAA) with radioactive sand in 60 feet of water indicate that transport processes and dispersion during disposal might cause displacement of up to 500 feet. Sludge has very small amounts of material as large as sand size and might be expected to sink more slowly and disperse more widely than the NOAA sand. Based upon preliminary laboratory experiments performed at Arthur D. Little, Inc. (ADL), it is believed that much of the sludge will not descend as individual particles. Assuming an average fall rate of 1/2 to 1/3 that of the NOAA sand, about 1,500-2,250 feet (0.25-0.37 nmi) of displacement might occur prior to deposit on the bottom in 90 feet of water. At the mud dump site, then, about 0.37 nmi could be accounted for in this manner. Bottom transport after disposal and initial deposition can be considered to account for the remaining displacement of 0.2-0.5 nmi.

Off the shelf navigational errors would be expected to account for ±2-3 nmi of scatter, unless special navigation equipment were required. If Loran-C, or equivalent, were required, navigational errors would be reduced to about ±0.25-0.5 nmi. Bottom transport processes would be expected to be less active, so the dispersion once deposition has occurred should be less than 0.2-0.5 nmi, perhaps 0.1-0.2 nmi. Transport processes and dispersion are assumed to be proportional to depth, so that in 1,000 feet of water they could account for 4.1 nmi as opposed to the 0.37 nmi estimated at the mud dump site in 90 feet of water. Adding these contributions, it is estimated that at an off-shelf dump site in 1,000 feet of water a high percentage of dumped sludge might accumulate within 6.2-7.3 nmi of the designated site (4.4-4.8 nmi if Loran-C navigation were required). Thus, the bottom area which might be affected by an off-shelf dump could range from 60 to nearly 170 square nautical miles.

In order to put these figures in some sort of perspective, assume that a maximum of 10-15 million short tons of dewatered sludge is produced annually along the Atlantic coast and it is deposited at a single deep dump site as a material containing 50% solids weighing 100 lbs/cubic foot. Some 11 million curbic yards per year would thus be distributed over at least 100 square nautical miles. This would amount to an estimated average annual accumulation of about one inch of sludge throughout the area.

b. Environmental Impact Potential

In general, the short-term effects of conventional dumping of FGD sludge in the upper water column (pelagic zones) of the deep ocean would be similar to effects described above for the continental shelf. The major differences between deep ocean and on-shelf disposal emerge in consideration of long-term benthic and food web impacts.

The wider dispersion that would be achieved by disposal in depths of several thousand feet would preclude many of the adverse impacts of benthic sedimentation associated with shallower on-shelf disposal. However, it is still possible that, given the lack of subsequent redistribution by storm waves in the deep ocean, sludge would comprise a substantial portion of the substrate in a deep ocean dump site. The advisability of deep ocean disposal from a benthic standpoint would then involve consideration of the trade-offs inherent in the preemption of the more diverse, more stable deep ocean benthic communities as opposed to the shelf communities. The latter are an integral part of the marine food web in which man is a high trophic level consumer. The deep ocean communities do not play such a role and, while unique, occupy a considerably greater percentage of the ocean floor than shelf communities.

The differences between deep ocean and on-shelf disposal regarding suspended sediment and sulfite impacts appear relatively minor. This is particularly true of the short-term impacts on the water column. Over the long term, sulfite would not be available to benthic finfish of direct commercial and/or recreational importance in the deep ocean.

Trace contaminant impacts would likely be less over the long term in the deep ocean. The impacts of dissolved trace contaminants in sludge liquors would be similar to those discussed above in conjunction with on-shelf disposal. However, two characteristics of the deep ocean dumping environment tend to mitigate trace contaminant impact potential. First, as noted above, deep ocean sediments appear to be a natural sink, exhibiting considerably higher concentrations of potential contaminants than near-shore areas. It may be that deep ocean benthic communities are tolerant of higher ambient concentrations of various contaminants but this is a hypothesis unsupported by empirical evidence at this time. Second, and more important, the lack of opportunity for contact between contaminants residing in the deep ocean benthos and food webs of importance to man would largely eliminate the risk of pollution episodes affecting human populations. Once again, the trade-off between impacting the relatively stable but areally extensive deep ocean communities would have to be weighed against these advantages.

2. Environmental Impact of Applicable Control Options

Disposing of only sulfate-based sludges in the deep ocean would serve to mitigate one of the remaining principal impact potentials, i.e., sulfite toxicity. Restricting the allowable sludges for deep ocean disposal on the basis of trace contaminant content is of lesser importance than for on-shelf dumping because of the considerable difference in long-term availability of such contaminants in the deep ocean. Overall, deep ocean disposal of sulfate-based wastes by conventional means appears to be a relatively viable option on environmental grounds.

Disposal by dispersion sufficient to achieve instantaneous dilution on the order of 5,000 to 10,000 also appears to be a relatively viable option from an environmental standpoint. These levels of initial dilution would mitigate suspended sediment and trace contaminant impacts, probably reducing them to insignificant levels. Potential problems of sulfite toxicity and/or oxygen demand in the upper water column would be mitigated but perhaps not resolved by deep ocean dispersal.

Disposing of chemically-treated, brick-like FGD sludge in the deep ocean is probably the most desirable of all options considered from an environmental standpoint. All of the major impacts discussed above would be substantially mitigated by this combination of controls. Economic considerations involved in this type of control scenario would be substantial and are discussed below.

The disposal of chemically treated soil-like FGD sludges in the deep ocean could mitigate sulfite impact potentials. Combined with dispersion, this would probably be a relatively attractive environmental alternative. However, as for the previous control option, economic feasibility is questionable and further discussed below.

E. ASSESSMENT OF TECHNOLOGY

1. Introduction

Three areas of technology related to ocean disposal of FGD sludge are discussed in this section: transportation, surveillance and navigation, and monitoring. The transportation section deals with pipeline and surface craft (barge and special vessel) transportation modes. The surveillance and navigation section addresses the accuracy and adequacy of methods available for monitoring the location and timing of dumping activities. Monitoring deals with the assessment of environmental baselines and trends in the ocean.

2. Marine Transportation and Disposal

a. Background

The vehicles and methods for ocean dumping are determined principally by the nature and form of the material to be disposed of and by the disposal site in relation to the site of receipt. Conversely, the nature and form of the material frequently may be changed to make it acceptable for use with a given transport system.

There are a number of viable techniques that would permit the bulk transportation of slurried mixtures to offshore disposal sites. The existing practical technologies allow controlled dispersal of the sludge over a great expanse of water, or a "sudden" total dump, or a continuous pipeline discharge of the material. The techniques would fall into the following categories:

- submarine pipeline transportation and dispersal at a preselected offshore disposal site;
- self-propelled hopper ship with throttled discharged disposal or with a sudden bottom dump capability; and
- tow-barge transportation and controlled dispersal over a great expanse of water or a sudden total bottom dump.

These varied approaches all are technically feasible systems which have been utilized full-scale. Selection among them depends upon the characteristics of the material to be dumped as well as upon the environmental conditions and constraints. In the case where the form and nature of the material--a deliverable for dumping--is predetermined or fixed, only the economics of the sea transport and disposal need to be examined.

In the case where a variety of forms of the material are possible, earlier elements of the system must be included in economic comparisons. For example, the total costs of bringing the material to the loading point, as well as loading costs must be included in the comparison. That is to say, possible transport/handling processes must be compared through all alternative transport/interface branches from a common starting point.

b. Pipeline Transport

For liquids of limited viscosity and for solids which can be particulated sufficiently to form a slurry the continuous-flow pipeline is mechanically the simplest and usually the most economic. Motive power, or flow energy, is provided by pumps. However, for large distances or in rapidly deepening water the capital cost of such a pipe installation may become predominant and the economics rapidly reach a cross-over point with other types of systems. The ecological effects of distributing the material must be considered in the light of the relative importance of benthic and nektonic biota, and in the light of the behavior of the material discharged from a single point, i.e., at the end of the outfall. For very heavy materials, insufficient velocity may be developed at the pipeline exit to produce sufficient dispersion; material buildups can occur at this point to make such a scheme impractical. In practice, physical model examinations may be required to determine critical velocities or appropriate dilutions of the material.

The U.S. Department of Interior, Bureau of Mines has conducted extensive research into pumping slurried coal through horizontal pipelines; however, the comparison between slurried coal and slurried flue gas solid/liquid waste is such that the developed data may not be compatible with the present need. It is likely that less than 50% solid to water ratio would be necessary for long distance FGD sludge transporting by pipeline.

The technology for underwater pipeline construction suitable to present needs falls into three categories: bottom pull, floating pipe, and lay barge pipeline positioning. Using the lay barge technique, the various oil companies have installed underwater pipelines of 30-inch diameter for distances as great as 108 miles. Other lines have been installed to sizes as great as 56-inch diameter. Once in position, it is normal engineering practice to protect the pipe from any vulnerable disruption. A pipe bury barge or jet barge is used to develop a trench.

The costs of offshore pipelines generally vary with length of the line, depth, pipe size, ocean terrain, and material to be transported. Typical complete installation costs for a 50-mile pipeline run about $550,000 per mile for a 30-inch diameter line and about $350,000 per mile for a 12-inch diameter line (in 1975 dollars). These estimates are based upon a 1974 study by the Oil and Gas Journal (13) and recent experience in pipeline transportation systems.

The greatest single cost factor in such pipelines is the installation cost which generally runs more than 50% of the total investment. Although right-of-way, material, and labor costs have risen significantly over the past few years, newer and faster construction/installation techniques have to a great extent tended to stabilize the cost per mile of pipeline.

Maintenance is a high cost factor in pipeline operation that is variable by location. Normally, the line is exposed to internal and external corrosion and internal clogging. External corrosion is combated with a bitumen, asphaltic, or coal tar material coating over which is installed a weight coating or concrete sheath. These coatings are used in conjunction with a cathodic protection system.

c. Transport by Surface Craft

The generalized alternative to pipelines lies in carriage of the material in batches by surface craft to a selected dump site and its release there. A prerequisite for surface release is that the material have a density greater than water--or in the case of inert or harmless materials, that it be soluble with a rapid natural rate of dispersion. The vehicle, i.e., the container for this transport of the material, may be a barge or a self-propelled craft. The material itself may be in any one of many forms. In general, economics demand that the material be carried in as concentrated form as possible and that the transport of large tonnages of water be avoided.

For materials heavier than water, direct release into the water column under gravitational force is possible. The discharge openings of the vehicle must be suited to particle size and desired discharge rate, and the process can be accomplished with a dry material which avoids carriage of large weights of water.

This type of dumping through openings in the bottom of the cargo enclosure of the craft brings about several practical considerations. The bottom of the cargo compartments, when the craft is empty, must lie above the light waterline of the craft. Otherwise, the compartment, open to the sea during the dumping, will partially fill with water. Even if a dewatering system (drains and pumps and overboard discharge) is fitted, large bottom doors or valves are difficult to maintain watertight. Thus, dump vehicles frequently are fitted with wing tanks and double bottoms to retain the cargo space above the light waterline. The openings themselves may be hinged doors, sliding doors, or conical valves moved axially in round seats. All three types have been used in self-dumping barges and scows and dredges.

In recent years a new dump scow concept has appeared in the form of the clam-shell barge. A hopper barge is split along a vertical longitudinal plane and the two symmetrical halves are hinged at deck level. Buoyancy compartments are arranged so that when the barge is loaded, a moment exists to open the joint; when the hopper is empty, a moment exists to snap the two halves shut. Thus, the mere release of a latch on a loaded barge causes it to open; the material drops through the entire length of the split in the bottom; and as the barge is lightened, the halves automatically shut and may be relatched. No power need be applied. Some of these craft are self-propelled with one "Harbormaster" or "Schottel" type of unit on each side of the stern.

In cases where the material is unsuitable or where operating conditions mitigate against the use of large hull openings and joints, the material must be lifted over the side of the craft and dropped into the sea. If a deck barge with bulwarks is used, the material can be shoved overboard through an opening in the bulwarks by some form of small bulldozer. From a hopper, methods as crude as the use of a crane and bucket are employed. The latter requires expenditure of considerable power, use of manpower, and is unsuitable in any sort of seaway. Less power and less attendance is required for pumping the material overboard, but in this case the material must be liquefied to the extent that a slurry is formed. Water can be introduced before or after loading, but in general this reduces the capacity of the vehicle for the material to be dumped. The introduction of water can be delayed until the time for actual discharge. The patented MARCONA ore transport system has a dry granulated mineral during sea transit; just before unloading, high pressure water jets in the bottoms of the cargo tanks enslurry the ore to a point where it can be pumped off the ship. Obviously, such a system raises initial costs and the operating cost of the craft, but its productivity relative to the basic material is greatly improved.

Tow-Barge Transportation

Open ocean towing requires special purpose equipment not normally found at many harbor locations where tow boats are usually of inner harbor design and usage. To make long-distance tows practical, a maximum payload must be transported and few barge lines can supply barges that have an American Bureau of Shipping ocean service classification.

The United States Coast Guard (USCG) has limited jurisdiction over tug boats and the commanding officer of such vessels can operate with a limited license restricted to tow boat operation, although most tow boat owners prefer a commanding officer with a captain's license. Tow boats, if under 300 gross tons, are not subjected to USCG inspections even though they may be capable of operating on an ocean route. The crews, however, cannot work more than an eight-hour day with the exception that if a trip is under 600 miles, the crew can operate on a two-watch basis, which means that a double crew is warranted on each tug boat. In such cases, all officers come under the federal competency requirements.

According to the USCG, a minimum crew would consist of two operators (navigators), two engineers, and two deckhands. At least one barging concern, though, indicates that safe and efficient operation calls for an additional deckhand and one or two cooks.

The speed of the tow is a variable factor, depending on barge size and weight, tug horsepower, and weather conditions. In general, tows can travel at average speeds of 3-4 knots to a maximum of 9.2 knots.

There are two large capacity bottom dump barges (the largest in the world) built in the United States which carry American Bureau of Shipping ocean-going classification--a 3,000-cubic yard (4,050-ton) barge and a 4,000 cubic yard (5,000-ton) barge. Such barges typically run $290 to

$350/dead weight ton (DWT), about $50/DWT more than simple hopper or tank cargo barges. Thus, these large barges would cost in the vicinity of $1,200,000 and $1,500,000 each, respectively.

Towing speeds (knots) for these barges would be as follows:

	Towing Speed (knots)	
Tug Horsepower	3,000-Cubic Yard	5,000-Cubic Yard
2,000	7.2	6.5
3,000	8.4	7.8
4,000	9.2	8.6

The barges have a longitudinally-divided hull, hinged at each end near the deck. Hydraulic cylinders provide the mechanism to open the lower hull and dump the sludge from within the hopper. The hull can be opened for a distance of 6 inches for slow in-transit dumping to 12 feet for a quick, sudden dump. The buoyancy force of the water, controlled by the cylinders, closes the hull after the load has been dumped. The dumping mechanism can be operated by means of radio remote control having the radio transmitter on the towing tug, thus providing complete automatic operation that would be necessary in the open ocean. The radio remote control system would cost $12,000 for each barge and would entail one transmitter on the towing vessel and one receiver on the barge that would be shipyard installed.

Self-Propelled Hopper-Type Ship Waste Disposal

The basic configuration of these vessels would resemble the hopper-type dredges owned and operated by the U.S. Army Corps of Engineers (currently, there are no industrially-owned hopper dredges in the United States), the exception being that the vessels would not require a dredging capability which involves expensive pumping systems and over-the-side dredge drag heads and suction lines. It must also be considered that the Army's hopper dredges are outdated and lack advancement in automation and dump hopper designs that have been developed in Europe and are now operational on many dredges.

The capacity of the U.S.-owned hopper dredges varies from a low of 720 cubic yards to a high of 8,277 cubic yards; however, European dredges have now reached 15,000-cubic yard capacity. To meet sludge disposal requirements, the capacity needed for each hopper ship should be at least 4,000 cubic yards. This meets the capacity of the largest available dump barges.

As discussed in Sections C and D above, the environmental impacts of sludge dumping in both raw or treated forms have implications on the types of transportation and disposal methods which might be suitable. If dilution of 1,000:1 to 10,000:1 can be achieved within a few (5-10) minutes, then dispersed disposal might be an option. If dispersed disposal is an option, it would more likely be applied over the continental shelf rather than in the deep ocean. Although the dispersal mechanisms would be very similar, economics would argue for the shorter haul distance.

The other option is treating sludge to create a hard (rock-like) form which could be hauled to the shelf and deposited to contribute to artificial reefs.

Application to Sludge Disposal

A bottom-dump barge (or self-propelled vessel) of the longitudinally-hinged variety could be used to transport and dump either partially dewatered, untreated sludge or treated sludge. A barge for handling untreated sludge would have to be specially constructed with a rubber seal at the lips of the bottom joint to prevent loss of sludge because of poor fit. However, this modification of available barges would probably be relatively inexpensive. In addition, it might be necessary to install special nozzles or other mechanisms for cleaning purposes. This could cause a maintenance problem and would be expensive if it were automated. If it were man-operated (and a barge rather than a self-propelled vessel were used), problems transferring a man from the tug to the barge at sea would be encountered. It is assumed that these problems have been overcome in the section which follows where comparative operating costs are calculated.

Sludge could be transported with a high water content (30% or less solids) and pumped directly overboard if it could be adequately dispersed and diluted in the wake of the vessel. A self-propelled vessel travelling at 10 knots covers 16.0 feet per second. For a cross-section of 30 feet x 12 feet the craft sweeps out 5,760 cubic feet per second. At a dilution of 10,000:1, an amount equal to about 0.6 cubic feet per second (about 2,000 cubic feet per hour) could be discharged overboard into this "wake." Assuming there are 21,000 cubic feet of solids onboard, discharge at this rate would take about 10 hours. This is feasible, provided a discharge system can be engineered to distribute the solids into the wake.

Alternatively, dry sludge could be transported and reslurried and diluted onboard. Preliminary calculations based on a 1,000:1 onboard dilution of dry sludge prior to discharge indicate that pumps capable of pumping over 300 million gallons per day would be required. Such pumping capacity is not feasible onboard a disposal vehicle.

3. Surveillance and Navigation

The impacts of ocean dumping of POD sludges will be some function of the geographic area touched by the disposal operation. To limit the impacts, the location of the dumping has to be controlled. There are two aspects of such control. The first deals with navigational accuracy available (or the ability to find any specified dump site with precision). The second deals with policing the operation to make certain that the dumping takes place at the specified location (within the accuracy limits of the available navigation systems).

a. Navigation System Accuracy

Piloting in inland waters using visual sights on fixed navigational marks has historically been the most accurate position-fixing means for ship navigators. Using these means, a ship's position could be located within several tens of feet. At sea the time-honored celestial navigation with dead reckoning can fix a ship's position within ±3-5 nmi, if done carefully.

At present, the Loran-A system provides electronic navigation coverage along all coastlines of the United States, the Great Lakes, Gulf of Alaska, Hawaiian Islands, and Puerto Rico. The position accuracy (±0.5 to ±3.0 nmi) is degraded under many nighttime conditions of operation, and the system is old and expensive to maintain. The Loran-A navigation system is to be phased out of operation over the next seven- to ten-year period.

In addition to Loran-A, over the past 25 years OMEGA, NAVSAT, and recently Loran-C have become available for use by commercial shipping. Loran-C now provides position accuracies of ±0.15 to ±0.5 nmi without degradation at sunrise and sunset. System improvements now underway are expected to provide a 15- to 20-fold improvement in position accuracies.

As of May 16, 1974, Loran-C became the Coast Guard's approved navigational system for the Coastal Confluence Zone (50 nmi from shore, or the 600-fathom contour, whichever is further from shore). At present, four Loran-C stations provide East Coast coverage. A new master station is now in operation at Caribou, Maine, which upgrades the accuracy of the East Coast Loran-C chain. Additional chains will be established in the Gulf of Mexico, on the U.S. and Canadian West Coast, and in the Gulf of Alaska to provide ±0.01 nmi position accuracy of the time. By the early 1980's it is expected that the upgraded Loran-C net will be operational, making position fixes within at least ±0.25 to ±0.5 nmi generally available to the shipping community within the area potentially used as an ocean dumping site.

Positional accuracies on the order discussed above are certainly adequate to the navigational requirements of dumpers. However, for the purposes of surveying and site monitoring, it may be necessary to achieve even greater accuracies in some instances, e.g., for work with submersible vehicles. Sonar transponder systems are available which allow a submersible to return to its exact previous position.

Where the bathymetry and the ocean monitoring stations in the disposal areas have been established with Loran-C time difference readings, the system provides an excellent capability to return to the original positions. Ship positioning tests in Boston Harbor by USCG 1st District Engineering Department personnel show that the Loran-C system can provide the Time Difference (TD) information necessary to return to a given position within about ±25 feet. With this system it can be expected, then, that where survey track lines and ocean station position information are tied to fathometer and bathymetric profiles in the usual manner, improved and repeatable position accuracies to within 50 feet can be achieved in future offshore ocean environmental monitoring programs using Loran-C.

b. Policing the Dump

The USCG is responsible for surveillance of ocean dumping under the Act and has relied upon a number of methods to carry out its responsibilities. Visual observation from ships and aircraft has been combined with ship riders and remote detection devices to monitor dumping operations. The initial USCG policy called for ship riders on about 10% of municipal waste and 100% of toxic chemicals disposal operations. This is an expensive procedure, and electronic means are being developed to replace the ship riders. In order to insure that dumping takes place at the EPA-specified location, such a system should include the following:

- continuous position information to and from the disposal areas available to the tug boat master at all times;
- an enabling signal to an interlock system that does not allow dumping until the barge is within the specified area; and
- a continuous analog or digital position and time record of ship position to be made availalbe to the USCG for inspection on completion of each trip.

The USCG is currently developing an Offshore Disposal Surveillance System (ODSS). The purpose of ODSS is to allow the USCG to determine whether the dump was actually made in the specified EPA disposal area at sea. After the tug and barge return to port, the USCG will inspect and analyze ODSS logs. The logs are to be recorded by ODSS and printed out automatically while the vessel is underway to show the track to and from the disposal zone and the ship's position while disposal operations are underway.

The ODSS system will use a fully automatic Loran-C receiver, data logger and recorder with a format on magnetic tape suitable for computer analysis by the USCG, if required. The system includes a dump status readout and a dump enable and control subsystem. The enable system is designed to inform the tow boat operator when the tow is in the dump area and to enable the dump control interlock system at that time. This allows the operator to commence dumping only when within the designated dump area. However, tow boat operators will have a manual override in case the system malfunctions.

ODSS system costs are projected by the USCG at under $10,000 for procurement and installation, all of which would be borne by the tug and barge ocean disposal company. Such equipment could be required before permits are issued.

4. Monitoring

a. Introduction

Monitoring of FOD sludge disposal at sea implies an oceanographic measurement program of some sort. As related to sludge disposal, there are two major categories of at-sea measurement programs which could be envisioned. First are those programs aimed at enabling better prediction of the behavior of sludge during and shortly after the initial dump. The second category deals with longer-term environmental baseline definition and trend monitoring.

The first category of measurements would focus on obtaining information for model development and validation. These programs might be very intensive in terms of observation platform (ships, buoys, aircraft, etc.) and personnel utilization. However, the duration of experiments would probably be relatively short, and they would not become routine or be repeated frequently. Such programs would require extensive planning and coordination beforehand, and significant amounts of laboratory and office analysis after the at-sea measurements. One can envision a great deal of effort being devoted to the identification, location, and study of the sludge plume *in situ*, possibly using tracers, drogues, high altitude photography, water samplers, turbidimeters, etc.

The second category of measurement program would focus on definition of the pre-dump and post-dump oceanographic environment in order to identify possible impacts. It is envisioned that such a program would be prescribed in detail as a condition on licenses for FOD sludge dumping in the ocean. It would undoubtedly incorporate a time series of oceanographic observations (probably seasonal), and the measurement program would become routine and focused on specific indicator organisms and sludge components.

b. Baseline and Trend Assessments

There are two principal types of environmental monitoring appropriate for the assessment of sludge impacts:

- the baseline assessment; and
- the trend assessment.

Baseline assessments are performed before beginning waste disposal operations and are generally considered to be synoptic surveys. A baseline assessment should be designed to provide a representative picture of the temporal and spatial range of existing marine environmental conditions over the period of measurement. Physical, chemical, and biological measurements are required.

The trend assessment results from analysis of the periodic and time-series data that are gathered in the disposal area after the disposal operation begins. The trend assessment information should be compared with control station data taken simultaneously at stations outside the disposal area, as well as with the baseline data taken before disposal operations began.

Assessments must be planned with the cooperation of federal, state, local, and private agencies and be documented and approved by EPA. Such approval will probably include the preparation of one or more Environmental Impact Statements for virtually all ocean dump sites presently in use or proposed for use.

c. Status of Instrumentation and Techniques

Some relatively sophisticated equipment has been developed for the measurement of important physical, chemical, and biological parameters in the water column and in the sediments of the ocean floor. Most deep ocean research and measurement activity has characteristically been carried out from research and survey vessels. Recent programs have utilized aircraft and even satellites to measure surface water temperature, and multi-spectral photography techniques have been used to locate and identify biological activity and pollution products on the ocean surface. Other programs have used manned submersibles for observations and for obtaining sediment and biological samples from the ocean floor. The NOAA Data Buoy Office (Bay St. Louis, Mississippi) has emphasized the development and placement of ocean buoys with instrument packages attached to the mooringline data line at fixed ocean depths where long-term time series measurement can be made. Each of these techniques may ultimately be useful in monitoring sludge dumping at sea. However, most baseline and trend surveys of ocean disposal areas will be sampling surveys carried out periodically from onboard ships.

Sensors to monitor meteorological parameters and the necessary physical oceanographic parameters of temperature, pressure, current velocity, etc. are in a good state of development and suitable for "baseline" measurements. Water samples, bottom grab samples, coring tools, and similar sampling equipment are readily available. However, sensors for continuous in situ monitoring of chemical and heavy metal pollutants for the most part are not available. It is necessary, at present, to take a sample of water, sediment, or refuse to a well-equipped laboratory for laboratory analysis using standard analytical techniques approved by EPA. Analysis of samples by UV (ultraviolet), IR (infrared), n.m.r. (nuclear magnetic resonance), spectrofluorometry, or gas chromatography are newer methods coming into very wide use. Such detailed analysis is time-consuming and expensive if large numbers of samples are evaluated on a routine basis. The development of simple biological and chemical sensors with high sensitivity, a broad range of response, and reliable long-term unattended operation is needed.

Most biological and dissolved-chemical measurements are made after water and sediment samples are collected using sample bottles of various kinds, net hauls, and bottom sediment grab and core samples. Samples generally are analyzed ashore or, in some cases, in a well-equipped laboratory area aboard ship.

d. Water Column Measurement

Water quality measurements to be made at various depths in the water column at each station include the following:

- temperature;
- salinity;
- dissolved oxygen;
- pH;
- light penetration;

- total organic carbon;
- inorganic nutrients; and
- suspended solids (or turbidity).

Analysis for selected heavy metals may be required at representative stations within the disposal area. Additional analysis of dissolved matter and particulates for constituents of FGD sludge may also be required. Special precautions and care must be taken to properly package samples for analysis later in the laboratory.

Sampling of the water column should be made at selected depths to identify changes throughout the water column that could be caused by the continued disposal of FGD sludge in any of its various forms. Sampling at depths represented by the following conditions is recommended (14):

- just below surface;
- middle of the surface layer;
- bottom of the surface layer;
- middle of the thermocline and/or halocline;
- just beneath the thermocline (near top of the stable layer);
- middle of the stable layer;
- as near bottom as possible; and
- near the center of any zone showing pronounced biological activity or lack thereof.

EPA (14) recommends that a minimum of five water quality sampling stations be made within boundaries of a dump zone. Additional stations would be required in areas larger than 20 square nautical miles in size. Additional sampling stations will also be required when local conditions (e.g., river outflows or strong ocean currents or occasional winds) cause an exaggerated distribution of ocean conditions.

Water Samples

Water samples may be collected at various depths using a variety of specially adapted water samplers. Although many specialized water samples have been devised for special purposes, the Nansen bottle and the Van Dorn type water samples are the most used in the United States.

The 1.25-liter Hansen sampler with the attached reversing thermometers is the most accepted equipment for obtaining water temperatures at selected depths and water samples for salinity, oxygen, silicates, alkalinity, phosphates, and other chemical analysis. The Van Dorn sampler is available in 1- to 5-liter and larger sizes and is used to provide large volume samples for trace analysis.

Where only temperature and salinity as a function of depth are required, more rapid and continuous profiles can be taken with the salinity, temperature, depth (STD) or conductivity, temperature, depth (CTD) instruments. The best of these equipments have been in wide use and are considered highly reliable measurement and recording equipments, e.g., Plessey 9040 series STD. Those devices are lowered on an electrical cable and data is recorded in digital and/or analog format in the shipboard laboratory. Typical operational specifications for these in situ measurement systems are:

- salinity = 0 to 40 o/oo ±0.02;
- conductivity = 0 to 5 mmho/cm ±0.002;
- temperature = -5 to +45°C ±0.02; and
- depth = 0 to 300 m ±0.5%.

Some newer equipments include additional measurements of water quality:

- pH = 2 to 12 ±0.1;
- dissolved oxygen = 0 to 20 ppm ±0.2; and
- turbidity = 0 to 100% ±3%.

Biological Samples

Biological samples can be collected with vertical and horizontal net tows as well as with conventional water samplers.

The Clark-Bumpus sampler is one type widely used for plankton net tows. It is towed at a chosen fixed depth, utilizes a fine mesh net, a plankton collection bucket, and an impeller and digital counter to measure the volume of water flowing through the net.

Mid-water and bottom trawls are used to work at depths below the thermocline to collect samples of larger organisms than those collected with the Clark-Bumpus sampler.

Analysis of the various nekton, phytoplankton, and zooplankton includes separation and cataloging in the laboratory according to dominant as well as sensitive, or indicator, organisms. Changes in the mix or populations of the indicator groups need to be carefully tabulated and compared with baseline and control station data.

Water Transparency

The penetration and absorption of light and the color and transparency of waters in and around an ocean dump area are measured with a Secchi disc or photometer.

The Secchi disc is a simple instrument which provides a relative, average index of the transparency of seawater near the surface.

The simple photometer measures natural light penetration. Some equipment provides for color filters that can be selectively triggered into place to determine light penetration as a function of depth. Alternatively, laboratory spectrophotometers and water samples are used for the same purpose.

The hydrophotometer or nephalometer measures light transmission over a fixed path length to determine the transparency of the water. Measurements can be made of the attenuation coefficient (a) or the scattering coefficient (k) which is a measure of water turbidity. Water turbidity measurements may be important for sludge monitoring. Color filters may be used to obtain spectral information.

e. Bottom Sampling

Inorganic waste deposits can modify the sediment structure of the sea bottom and change the composition of benthic communities. Therefore, the size distribution, mineral character, chemical quality, and biota of the sediments in the proposed disposal area must be assessed.

Benthic biota can be collected with a dredge, or bottom grab sampler. There are a variety of grab samplers (e.g., Orange Peel Bucket Sampler, the Clamshell snapper and the Van Veen bottom sampler) that are useful for obtaining samples of surface sediments and benthic biota from a hove-to survey vessel. None of them provide an undisturbed sample showing structure and microlayering.

Coring devices are designed to penetrate the bottom sediments from 1/2 to 10 or more meters to obtain relatively undisturbed core samples. Generally, for ocean disposal area surveys, core lengths of 1/3 to 1 meter will be required.

Gravity-type and piston-type corers are available for this purpose. Each depends on gravity to penetrate the ocean floor after a release mechanism has been tripped. Several piston-type corers have been developed to retain nearly undisturbed core samples. Commonly used coring devices are:

- Phleger gravity corer - core lengths 1/3 to 1 meter;
- Kullenberg piston corer - core lengths 1 to 20 meters; and
- Hydro-Plastic (PVC) Piston corer - core lengths 1 to 6 meters.

The Phleger gravity corer is widely used and provides sample materials suitable for most baseline programs. The PVC Piston corer type device is preferred where relatively undisturbed core samples are required.

When the sample materials are retrieved on deck of the survey vessel, they must be handled and packaged by approved methods for analysis later in the laboratory. Tissue samples may have to be analysed for heavy metals. Where benthic organisms are to be counted and classified, contamination of the sample must be minimized.

At a station located near the center of the ocean disposal area, bottom sediment data should be taken and analysed for selected heavy metals including: arsenic, beryllium, boron, cadmium, cobalt, copper, lead, mercury, nickel, selenium and zinc. These samples require precise analytical techniques and, in some cases, special laboratory analysis equipment. The samples must be preserved for subsequent analysis.

f. Bathymetric Survey

Bathymetric survey lines are generally run in rectangular grid patterns to develop bottom topographic coverage sufficient to allow contours to be determined at intervals of 1 fathom (6 feet) or less. Loran-C navigation control should allow for spacing of tracklines to about ±50 feet (if required) in most offshore areas.

The requirements and specifications for each bathymetric survey vary depending on the trackline control available, the bottom topography, water depth, and on the chart scale required. In most cases, charts of 1:25,000 to 1:10,000 will be required to show a 1- to 3-meter contour interval except in very flat areas. Surveying instruments (precision fathometers, side scanning sonars, etc.) are sufficiently developed to meet the bathymetric monitoring needs associated with FGD sludge disposal.

g. Current Measurements

Many types of instruments have been developed over the years to measure the speed and direction of ocean currents at different depths in the water column and near the bottom. These devices range from simple drift bottles and drogues to very sophisticated telemetering electronic systems tethered from a ship, surface buoy, or buoyed from the bottom on a taut line.

There are, in general, two broad categories of ocean current measurement instruments in wide used:

- free-floating; and
- fixed.

Those in the first category (free-floating) are useful for determining water mass movement and general surface and near surface current patterns in coastal areas. Surface floats, dyes, and mid-water parachute drogues are commonly used for this purpose. The second category (fixed) includes instruments that are attached to fixed and floating structures such as piers, towers, tripods, placed on the ocean floor, or more commonly, tethered from survey vessels and buoys. This second category includes mechanical devices and sophisticated electronic equipments. In baseline and trend measurements these instruments are tethered on a line from a ship or buoy and record the information on strip chart, magnetic or paper tape, or telemeter the information to a recording station ashore or to a nearby surface ship.

Free-Floating Current Measurements

Drift bottles (sealed bottles with a return post card inside) or drift cards and dye markers are commonly used to show the general movement of a water mass. Visual means are generally used, but color photography from overflying aircraft or fluorometric measurements are more sensitive means of following the dispersion of the dye in the water mass.

Parachute-type drogues have been used for many years to track submerged currents and, in some cases, deep countercurrents. They are effective for short-term tagging and tracking of a particular water mass.

Fixed Current Measurements

A variety of current meters have been designed for this purpose over the years. The Richardson-type or Hydro Products 650 series profiling-type current meters are examples of newer equipments which utilize a Savonius rotor to obtain current speed over a wide range from 0.1 to 5 knots. A small vane orients itself with the ocean current to within ±10°. The speed and direction information is digitized and recorded on film to be evaluated after the current meter is retrieved. Other modern ocean,current meters record speed and direction data in situ on strip chart, magnetic tape, or telemeter the information in digital form over a wire link to a surface vessel or shore station. Such information may also be transmitted in a computer comparable digital format for immediate display and analysis.

The major difficulties with current meters of this type are their inability to completely resist corrosion and fouling, resulting in degradation of performance. In long-term measurements these factors can severly reduce accuracy and precision of sophisticated equipment, particularly at low current speeds. Clearly, a careful calibration of equipment is required both before and after deployment to account for any degradation in performance during the survey operation.

Other errors besides those of corrosion and fouling are prevalent in the use of wide range ocean current meters. One of the most common of these is platform movement which tends to tow the current meter through the water and indicate false current speed and direction components. Precision navigation information can help compensate for this error.

h. Survey Time and Cost Estimate

The cost of producing baseline and trend surveys at coastal offshore waste disposal areas varies with the sampling frequency and duration, size of the area, its bathymetry, bottom topography, weather conditions, and the amount of detail required. Ocean areas near fishing areas or known spawning grounds may require more detailed survey information than areas located in less valued locations. Also, if the proposed disposal area is near shore and there is the risk that waste materials might contaminate beaches, salt marshes, or other recreation areas, a more extensive survey and data reduction program may be required. The emphasis and time spent on the assessment of various aspects of the environment will depend on the type and quantity of sludges proposed for disposal at the site and also on the potential for effects on the local and surrounding environment.

Timing and Duration

Baseline and trend surveys must be conducted to account for seasonal variabilities in environmental conditions at the site (e.g., ocean currents, wind, and meteorology).

In some disposal locations the initial surveys may show that seasonal variations cause no significant changes in the environment at the disposal site. As a result, surveys at greater than seasonal intervals may be scheduled, but an effort should be made to conduct the trend surveys in climatic conditions as near those of the baseline survey as practical.

The time required to complete a field survey will depend mainly on the complexity and size of the proposed site as well as upon the types and variety of data to be collected. The bottom topography and hydrography will in large part determine the number and location of the bottom sampling stations. EPA (14) recommends that the ratio of bottom stations to water column stations should be about 3:1, depending upon the site being evaluated. Additional bottom sampling stations are needed when there are large discontinuities in the bottom topography, and stations should be set to provide representative bottom samples on each side of a discontinuity. The number of bottom stations required will also depend on how well the FGD materials dissolve before reaching the bottom and also whether the sludge is in a treated form intended to dissolve slowly on the bottom. With consistent bathymetry devoid of canyons and rifts, the sampling stations can be uniformly distributed throughout the area. Additional control stations (upstream and downstream) should be included.

A baseline survey of this magnitude could generally be expected to require up to 18 months to complete. One cruise might last one to three weeks. Trend assessments will be required at the FGD disposal site three to four times per year after FGD disposal begins. Additional surveys of selected critical parameters may be necessary during periods of heavy dumping.

Cost Estimates

The cost of conducting site surveys will vary with many factors, including the location and proximity of the site to shore, size of the area, depth of water, bottom topography, and most important, the complexity and detail required of the analysis. In addition, bad weather conditions, such as heavy seas, can significantly lengthen the time required to make the measurements and acquire the necessary samples at sea. Because of these factors it is difficult to generalize the cost estimates and time required to perform a survey. Some useful guidelines might be as follows.

Most baseline and trend surveys are made with small survey vessels 90 to 180 feet in length. Average daily costs for a survey vessel completely fitted out with the required measurement, survey, and deck handling equipment is in the range of $2,000 to $2,500 per day. One to three weeks of ship availability is generally required to complete a site survey which allows for mobilization and demobilization time necessary to make a leased vessel suitable for the survey work required.

The number of ocean measurement stations varies, as discussed above. In ocean disposal areas the density of ocean stations may vary from about one station per two square miles to about one station per five square miles. In near-shore areas, for example, where river outflow, tidal currents, or strong localized ocean currents are a significant factor in determining potential ocean dumping impacts, an even higher density of ocean sampling may be justified.

Physical data from oceanographic survey stations is, in large part, tabulated aboard ship before the ship leaves the area. The chemical, biological, and sediment oceanography is, in large part, evaluated in analytical laboratories ashore. It is this detailed laboratory analysis and reporting of all data that is the most costly and time-consuming part of an ocean dumping site survey operation. The detailed laboratory analysis work may require many times the ocean disposal site survey time to complete, depending on the complexity, detail, and quantity of data and samples to be analyzed and evaluated. For example, highly selective hydrocarbon analytical techniques that use the powerful combination of gas chromatography and/or mass spectrometry can determine the presence of chemical groups within the sample and may add an additional $500 to $1,000 per station. A final report and interpretation of ocean disposal site environmental data may require nine months to a year before it can be completed, reviewed, and released.

Recent experience indicates that offshore ocean dumping site surveys that require one to two weeks of ship time to complete will require an additional three to four months for data evaluation, analysis, and reporting. A typical ocean survey program of this type can cost [illegible] the range of $200,000 to $250,000 per cruise including preliminary conclusions and a summary data report.

F. CONCLUSIONS AND RECOMMENDATIONS

1. Technical/Environmental Considerations

Two major overall conclusions emerge from this assessment of the disposal of FGD sludges in the ocean. First, there is an overriding need for case-by-case analysis of the environmental feasibility of ocean disposal of specific FGD sludges. The emphasis in such analyses should be twofold, focusing both on the type of sludge and disposal site environmental conditions. Second, control options involving chemical treatment of sludge, limitations on the type of sludge disposed of, and control of the method of sludge placement (either dispersed or concentrated bottom-dump disposal) all appear to be technically feasible. Economic feasibility, however, is less clear-cut and would serve to limit the viability of several of the most promising environmental options.

Specific conclusions are as follows:

- Unless further work contradicts the anticipated sedimentation and suspension impacts, the disposal of untreated or treated FGD sludges with soil-like physical properties by bottom-dump barge or outfall on the continental shelf must be considered to be environmentally unacceptable.
- Based upon available information on sulfite toxicity, it appears that an almost immediate (on the order of minutes) dilution factor greater than 10,000:1 for sulfite alone is required in the dispersed disposal of untreated sludges

containing large fractions of sulfite. The technology is not currently available for attaining such dilution factors for untreated sulfite-rich sludges in an economical manner. Therefore, the dispersed disposal of sulfite-rich sludges, both on and off the continental shelf, is not considered to be a promising option at the present time. Further information on organisms uptake and toxicity of TOS would justify reevaluation of this conclusion.

- Several disposal options appear promising and are recommended for further research. These include:
  - dispersed disposal of untreated sulfate-rich FGD sludges on the continental shelf;
  - concentrated disposal of treated brick-like FGD sludge on the continental shelf;
  - dispersed disposal of untreated sulfate-rich FGD sludges in the deep ocean; and
  - concentrated disposal of both untreated sulfate-rich FGD sludges and treated FGD sludges in the deep ocean.

  Recommended additional research is discussed in more detail below.

2. Regulatory Considerations

In general, given the present vigilance in agency attitudes towards ocean dumping, the existing regulations appear to be adequate to insure protection of the ocean environment. However, several specific recommendations are considered appropriate at this time. These are as follows:

- Pending revisions to the existing ocean dumping regulations that would allow for additional empirical considerations (e.g., field data and models) in the determination of limiting permissible concentrations in the ocean at the disposal site should be adopted.
- Existing absolute limits on permissible concentrations of mercury and cadmium in solid fractions of wastes should be reevaluated through consideration of the actual anticipated long-term availability of the contaminants on a case-by-case basis.

- Inherent disincentives to deep ocean dumping (e.g., extra monitoring requirements) should be reevaluated in light of the apparent desirability of certain deep ocean disposal options.

There appears to be no need for additional sludge-related legislation concerning ocean disposal at this time.

3. Need for Additional Research and Information

The following research needs are believed most important at this time.

- A body of empirical data needs to be developed concerning the chemical and physical fate of sludge in seawater. Of particular importance are:
  - dissolution rates of various treated and untreated FGD sludges in the representative types of seawater that would characterize the disposal area environs; and
  - physical transport of both treated and untreated sludges in the water column during descent and subsequently in the marine benthos (near the bottom).

  These effects will be studied in laboratory-scale testing with untreated sludges during the Phase II program.
- A body of empirical data needs to be developed regarding the biological impacts of sludge disposal. Specifically:
  - uptake of both liquid and solid constituents of FGD sludges by various marine organisms need to be developed;
  - in particular, for uptake associated with short-term exposure of pelagic organisms; and
  - lethal and sub-lethal effects thresholds need to be developed for exposure of a variety of representative marine organisms to FGD sludges (one of the focal points of such research should be the dynamics of food web transfer of potential toxicants).

  The investigation of such biological impacts is planned for the simulation/demonstration testing in Phase III.
- Mechanisms for eliminating existing economic disincentives to deep ocean disposal should be developed. These could include consideration of such options as a greater federal role in baseline and disposal area monitoring.

GLOSSARY

antagonism -- In a toxicological sense, an interaction between two or more substances which results in less damage potential than would be expected based on the hazards posed by the individual substances. In other words, the combination tends to suppress toxic effects.

attenuation coefficient -- A measure of the space rate of diminution (or attenuation) of transmitted light.

bathymetry -- The science of measuring ocean depths in order to determine the sea floor topography.

benthic (benthos) -- As an adjective, used to describe organisms, events, or other aspects of the environment found near and including the bottom of a water body. The noun (benthos) is usually used to describe the organisms residing in this part of the water column. Macrobenthic refers to the subset of benthic organisms that are large enough to be examined with the naked eye.

bioassay -- A test in which one or more living organisms is subjected to stress under controled experimental conditions.

biological concentration -- A process whereby living organisms extract substances from the surrounding environment and incorporate these substances or forms thereof within their tissues.

biomass -- The weight of living organisms in the population or community under study.

calanoid copepod -- Any of the order of microscopic crustacea which commonly are among the dominant zooplankton in estuarine and coastal waters.

control -- As in "control location;" an adjective used to describe the location or set of conditions experiencing all aspects of the situation under study, *except* the experimental variable. In ocean dumping situations a control location might be one where no ocean dumping has taken place.

detritus (detrital) -- A term used to describe decaying organic matter, especially decaying vegetation.

drag heads -- The working element of a hydraulic or hopper dredge which sucks up sediment off the bottom of a waterway.

drogue -- A current measuring assembly used to "catch hold" of a parcel of water in order that the water may be tracked over a period of time. Often consists of a weighted parachute or a pair of crossed wooden or metal plates.

ecosystem diversity -- As used in the Marine Protection Research and Sanctuaries Act of 1972, a general term to indicate the amount of variety in types of organisms and communities in the marine environment.

ecosystems dynamics -- The processes of interaction between organisms and their environment.

faunal assemblages -- Groups or communities of animals, usually used in reference to a group of several different species typically found together.

food web -- A term used to describe the network of relationships between various organism populations and their food supplies.

gravity corer -- Any type of corer that achieves bottom penetration solely as a result of gravitational forces acting on its mass.

halocline -- A well-defined, vertical gradient of salinity which is usually positive.

"Harbormaster" unit - A semi-portable ship propulsion unit resembling a large outboard motor.

hove-to -- The condition in which a ship is kept headed into the wind with no headway or by working the engines as necessary.

in-situ -- A Latin term meaning in place or in the natural or original position.

indicator organisms -- Under experimental or field observation conditions, indicator organisms or species would be the forms expected to first react to the experimental stress under study.

isopach -- A contour line on a map drawn through points of equal thickness of a sedimentary layer.

Loran -- A long-range electronic navigation system which uses the time divergence of pulse-type transmission from two or more fixed stations-- Loran-A was the original operational system; Loran-C is a system with improved reliability and accuracy.

macrofauna -- Animals large enough to be readily seen with the naked eye.

mooring-line-data-line -- A specially designed electrically insulated data-buoy mooring line through which oceanographic sensors transmit data to the buoy for storage.

multispectral photography -- Simultaneous photography of subject matter through different colored filters to enhance the capture of spectral information.

Nansen sampler (Nansen bottle) -- A device used by oceanographers to obtain subsurface samples of seawater.

NAVSAT -- A Navy-developed satellite navigation system.

nekton -- A term used to describe those organisms, such as fish, capable of extensive voluntary movement in the water column.

OMEGA -- A low frequency electronic navigation system.

pelagic -- An adjective used when referring to areas or organisms characteristic of the open ocean, particularly upper layers of the water column in contrast to "benthic."

pelecypod mollusks -- Any of the class of shellfish often referred to as bivalves, including the commercially valued forms of clams and oysters.

phytoplankton -- Floating plants, often microscopic.

piston-type corer -- A corer equipped with a piston inside the core tube that is attached to the lowering cable. When the corer penetrates the ocean bottom, the piston provides suction to counteract the friction between the sediment and the wall of the core tube.

plankton -- Free-floating organisms, usually microscopic, and incapable of extensive voluntary movement in the water column.

polychaete -- Any member of the class of marine and estuarine worms, typically among the most abundant organisms in coastal benthic communities.

Savonius rotor -- A current meter rotor responsive to a wide spectrum of horizontal flow components, built in the shape of two semi-cylindrical vanes disposed to form an S.

scattering coefficient -- A measure of the attenuation due to scattering of radiation as it traverses a medium containing scattering particles.

"Schottel" unit -- See Harbormaster unit.

seaway-- A marine highway.

sonar transponder systems -- Navigation aids based on the employment of underwater sound.

STD -- An instrument which measures and records salinity, temperature, and depth simultaneously.

stress -- In ecological terms, any condition which could serve to limit a biological function.

sublethal -- An adjective used to describe a condition, usually a stress, that has some adverse effect other than death. The term is often used to describe a concentration of a substance in the environment at which organisms would survive but experience some measure of adversity.

thermocline -- A vertical negative temperature gradient in a body of water which is appreciably greater than the gradients above and below it.

tracklines -- Lines on a chart depicting the locus of points where scientific measurements (e.g., depth, gravity, magnetic field) have been made by a ship underway.

upwellings -- The process by which water rises from a lower to a higher depth, usually as a result of divergence and offshore currents.

Van Dorn sampler -- A device used by oceanographers to obtain subsurface samples of seawater. Usually made of plastic and larger in capacity than Nansen samplers.

zooplankton -- Floating animals, usually microscopic.

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VII. DISPOSAL SYSTEM COSTS

A. BASIS FOR DESIGN AND ECONOMICS

Conceptual system designs and general capital and operating costs have been prepared for a number of feasible ocean and mine sludge disposal options. Table VII-1 summarizes the sludge basis, and Tables VII-2 and VII-3 show the assumptions and factors used in the cost estimates.

Costs are based upon the disposal of sludge produced at a 500-megawatt power plant operating at an average annual load factor of 80% and burning typical eastern high-sulfur coal (3.0% sulfur, 10% ash, and 0.85 lbs of coal per kilowatt-hour). The rate of sludge production is estimated for 90% SO_2 removal using a well-run direct lime scrubbing system with fly ash removed upstream of the scrubber system by a highly efficient electrostatic precipitator.

General sludge characteristics, as discussed in Chapter IV, have been used. In all cases, the sludge is considered to consist of the combined ash and calcium-sulfur salts from SO_2 removal. For the purposes of this study it is assumed that the sludge is available in the form required at the FGD system battery limits. No costs have been included for any type of sludge processing, such as filtration, drying, fly ash addition, or chemical treatment.

B. COAL MINE DISPOSAL

Conceptual designs and costs have been prepared for four basic transport/disposal operations for onsite and offsite mines--two each for surface area and underground room and pillar mines. Offsite mines have been assumed to be 200 miles from the power plant; onsite mines, four miles from the power plant. For offsite mines, rail haul is assumed to be the basic mode of transport for the sludge. Initial estimates show truck haul and slurry pipeline to be impractical over such distances. For onsite mines, truck haul and pipeline transport are used.

1. Description of System Operations

a. Surface Mine Disposal

The two basic transport/disposal systems evaluated for surface area mine disposal are shown schematically in Figure VII-1. For each system,

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TABLE VII-1

SLUDGE BASIS FOR CONCEPTUAL DESIGN

Boiler:

capacity = 500 Mw
load factor = 80% annual average

Coal:

0.85 lbs coal/kwh
3.0% sulfur
10% ash

Pollution Control:

90% SO_2 removal (scrubber)
99+% particulate removal (ESP)

Sludge Production (thousands of short tons per year):

Annual:	dry SO_2 sludge	225
	dry ash	140
	dry total	365
	wet total (@ 50%)	730
Daily Average:		2,000 (wet)
Daily Peak:		3,000 (wet)

TABLE VII-2

CAPITAL COST BASIS
(1977 Completion, 30-Year Life)

Capital Investment Includes (battery limits - FGD system):

- Installed Equipment Cost (IEC)
- Engineering and Fees
- Startup
- Working Capital
- Owner's Expense (@ 8% of IEC)
- Interest During Construction (@ 15% - two years)
- Escalation During Construction (@ 8% - two years)

Capital Investment Does Not Include:

- Extensive Site Preparations
- Sludge Processing
- Provision for Utilities
- Land
- Mine Fees (if any)
- Permit Associated Costs

TABLE VII-1

COST FACTORS

Item	Unit Cost
Variable:	
Power	$0.015/kwh
Diesel Fuel	$0.40/gal.
Labor:	
Direct	$8.00/manhour
Overhead (supervision & fringes)	70% of Direct Labor
Maintenance	2-5% of Installed Equipment Cost
Plant Overhead	40% of Direct Labor & Maintenance
Capital Charges (depreciation)	17% of Total Installed Cost
Interest/Insurance/Taxes/Fees (rolling stock)	10% of Equipment Cost

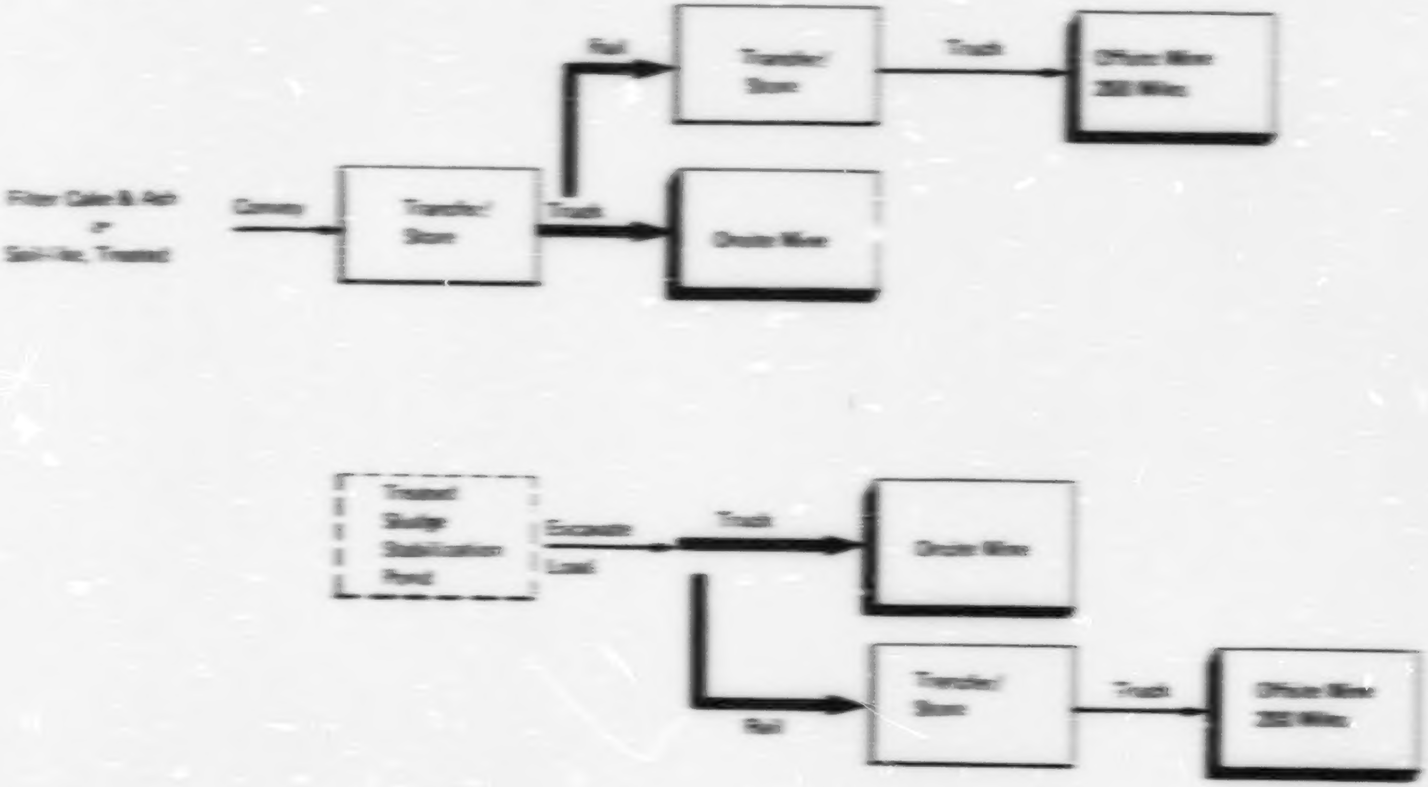
Filter Cake & Ash
or
Soil-Fix, Treated
Convey
Transfer/
Store
Rail
Truck
Transfer/
Store
Truck
Offsite Mine
200 Miles
Onsite Mine
Treated
Sludge
Stabilization
Pond
Excavate
Load
Truck
Onsite Mine
Rail
Transfer/
Store
Truck
Offsite Mine
200 Miles

FIGURE 7-1 SURFACE MINE DISPOSAL OPERATIONS

estimates have been prepared for handling both dry filter cake admixed with ash and stabilized, treated sludge (processing costs not included).

Onsite Mine-Truck Haul

Either well-filtered sludge mixed with fly ash or stabilized, treated sludge could be disposed of in a surface area mine. The transfer, handling, and placement systems would be almost identical; except with treated sludges requiring stabilization ponds, there will be the added cost of excavating the ponds.

There are many possible system configurations for handling and transferring filter cake and ash, depending upon the need to control the filter cake/ash ratio and the manner in which fly ash collection and filtration systems are operated. It has been assumed as a basis for the conceptual design that the fly ash/cake mixing system could be run independently of the disposal operation so there would be need for storage of the mixed cake and ash. The sludge leaving the cake/ash mixing area would be transferred via belt conveyor to a covered transfer/storage area where an intermediate stockpile would be maintained. The sludge would then be loaded into rear-dump trucks using front end loaders.

The rear-dump trucks would transport the sludge to the mine (four miles) and dump the sludge in the mined-out pit prior to replacing overburden. In a typical Interior mine the principal coal seam varies from three to ten feet thick, so the layer of sludge, which amounts to only about 40% of the coal seam by weight (3.0% S, 10% ash), would be no greater than a few feet deep. Thus, there would be no need to level and compact the sludge with earth-moving equipment to provide a base for trucks so that the layer could be built up. The operation, therefore, would require six 35-ton trucks (one spare) and two 3-cubic yard front end loaders (one spare) to handle the sludge on a one-shift per day basis).

Treated sludges could be available either as a soil-like material at the battery limits of the treatment plant or as a hardened product in a stabilization pond which would require excavation. For the soil-like material the cost structure for untreated filter cake mixed with ash is assumed. For treatment involving ponding a three-pond batch system is envisioned (one being filled, one stabilizing, and one being excavated).

It is assumed that a Sauerman-type system could be used for excavation and that it could operate on a regular one-shift basis (8 hours/day, 5 days/week, 50 weeks/year). Excavated material would be transported via conveyor to the transfer/storage area.

Offsite Mine-Rail Haul

For offsite mine disposal the sludge would be conveyed to a transfer/storage area where it would be stockpiled as previously described. At the transfer area the sludge would be loaded into feed hoppers via front end loaders. The hoppers would be located over the existing rail line "down track" from the coal unloading area and would discharge directly into the rail cars. We have assumed two feed hoppers and two front end loaders in order not to unduly delay the train.

The train would transport the sludge in uncovered cars, 200 miles to the mine. Since rail rates do not exist and are difficult to obtain for sludge, we have estimated a rate of $2.00/short wet ton (1¢/ton-mile) based upon existing rates for coal, gypsum, and sand and gravel and taking into account that the cars normally return empty.

At the mine site the train discharges 6,000 tons of sludge every other day. The sludge is dumped into a hopper under the track and then conveyed to a covered storage/transfer area. The cars then proceed to a wash-out pit where water sprays wash any sludge adhering inside the cars. The waste slurry from the washing operation is pumped to the disposal dam along with the fine tailings from the washing plant.

At the transfer/storage area the sludge is loaded into rear-dump trucks using a front end loader on a regular one-shift per day basis to coordinate with the mining operation. The dump trucks then deliver the sludge to the mined-out pit. A two-mile haulage distance (one way) has been assumed. Since this is a shorter distance than for the onsite mine case, only three trucks and one front end loader are required.

b. Underground Mine Disposal

For underground disposal we have selected hydraulic filling of abandoned or mined-out sections of an Interior coal mine using a slurry containing 25-30% solids. The disposal operations are shown schematically in Figure VII-2.

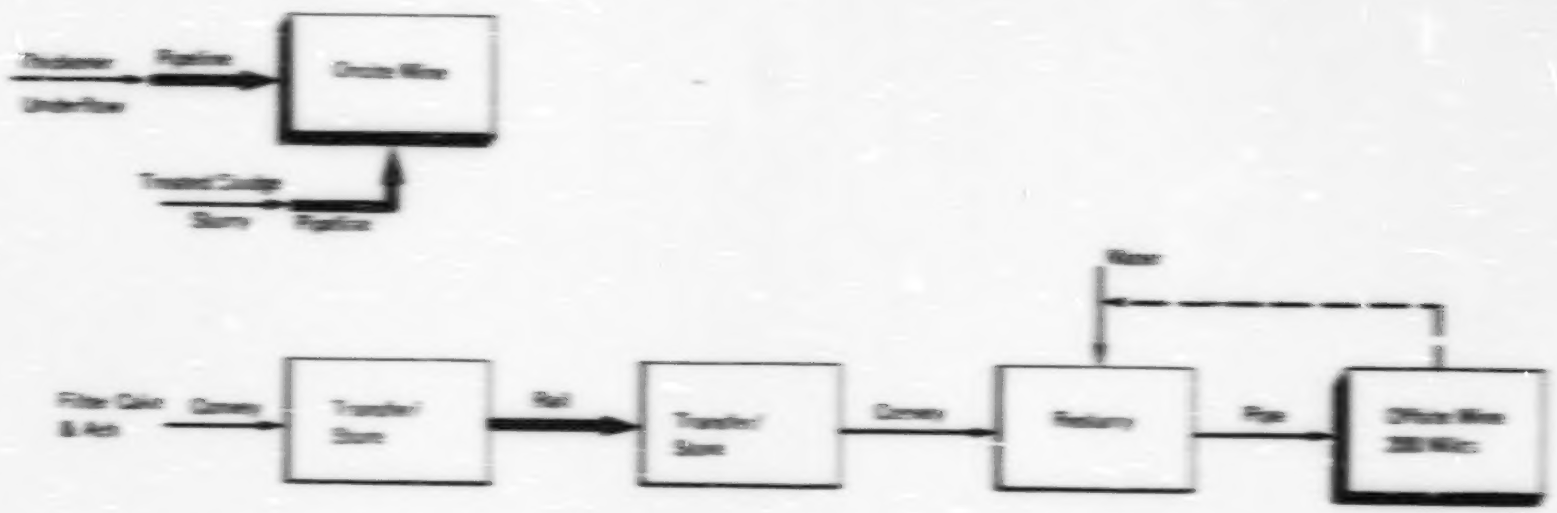
Thickener
Underflow
Pipeline
Onsite Mine
Treated Sludge
Slurry
Pipeline
Water
Filter Cake
& Ash
Convey
Transfer/
Store
Rail
Transfer/
Store
Convey
Reslurry
Pipe
Offsite Mine
200 Miles

FIGURE VII-2 UNDERGROUND MINE DISPOSAL OPERATIONS

Assuming that the mine has a seven-foot coal seam 800 feet below ground and that the sludge will settle to 50% solids (with the excess water pumped out), the mine area required (with 60% coal extraction) will amount to about 90 acres per year. Bulkheads would be required on three sides containing a maximum of about four acres, with one 4-inch borehole (cased) for each disposal cell. Bulkhead and borehole construction is assumed to proceed continuously.

Onsite Mine-Pipeline Transport

Where the power plant is located at the mine mouth, the scrubber bleed can be pumped to the mining area where it is then thickened. The underflow (20-30% solids) would then be pumped down the boreholes and the overflow combined with mine pump-out and returned to the scrubber system. It would also be possible to treat the sludge after thickening and prior to disposal, as long as a "wet" treatment system were used and the resulting unstabilized sludge could be easily pumped. However, it would probably not be possible to return mine pump-out to the FGD system, and care would have to be taken to minimize plugging of lines due to slow setting of the treated slurry on the pipe walls. Since it is impossible to estimate the cost for handling treated slurry without more definitive data, it is assumed that the costs for disposing of thickener underflow or repulped filter cake would apply in general to treated slurry.

For disposal costs, only the incremental costs to the FGD and treatment systems have been included--that is, the cost of the pipelines between the thickening system and the FGD system, and the mine disposal piping and bulkhead construction. As a cost basis we have assumed a two-mile distance from the thickening area to the FGD system and an additional variable distance ranging from a few hundred feet to a mile between the thickener and the disposal boreholes (with the distance increasing over the 30-year life of the mine and power plant). No sludge, slurry, or clear liquor storage is assumed other than that provided by the thickener and the thickener hold tank.

Offsite Mine-Rail Haul

Since it would not be economically attractive to pipe slurry (either thickener underflow or scrubber bleed) over great distances, for offsite mine disposal, rail haul of filter cake (with ash) and reslurry at the mine for hydraulic backfilling has been assumed. The system would essentially be a combination of that described for offsite surface mine disposal (between the FGD system and the mine storage area) and the onsite underground mine case. It would involve conveying the sludge to a storage/transfer area, loading rail cars and hauling to the mine, dumping the sludge and conveying to a second storage transfer area, conveying to a repulping tank, and pumping down the boreholes. The mine pump-out could be used for reslurrying the sludge.

2. Cost of Disposal Operations

Table VII-4 gives a summary of the cost estimates for these six mine disposal options based upon the cost factors provided in Tables VII-2 and VII-3. Note that these costs do not include monitoring. Monitoring costs will depend strongly on the local/regional hydrology and the parameters (species) monitored, and are not necessarily a direct function of the quantity of sludge handled. Therefore, it could be misleading to directly assess monitoring costs on the basis of tons of sludge handled. It would be anticipated that the cost of monitoring a typical Interior surface area mine disposal operation could run on the order of $500,000/year, including sludge characterization, sample well location, analysis of both core and water samples, and inspection of the disposal operations.

As would be expected, disposal of untreated sludge or treated, soil-like sludge in onsite mines provides the least expensive system, with cost estimates of $1.00-1.50/ton of dry sludge. Offsite disposal in mines increases costs to $6.50 to $8.00/ton of dry sludge. Disposing of treated sludge from stabilization ponds increases costs roughly an additional $2.20 to cover the cost of excavation. Again, it should be noted that these costs do not include any processing costs for the sludge other than pond excavation. Filtration and admixing with ash or treatment additives is not considered.

C. OCEAN DISPOSAL

Conceptual system designs and associated cost estimates have been prepared for five ocean disposal systems off the East Coast--two for on-shelf (shallow ocean) and three for off-shelf (deep ocean) dumping. The five alternatives are shown schematically in Figure VII-3.

TABLE VII-4

CAPITAL AND OPERATING COSTS FOR MINE DISPOSAL ALTERNATIVES

Mine Type	Location	Sludge Type	Principal Transport Mode	Capital Cost ($MM)	Operating Costs[a] ($/dry ton)	Operating Costs[a] (mills/kwh)
Surface (truck dump)	Onsite	Filter Cake + Ash Soil-like or Treated	Truck	1.85	3.30	0.35
		Treated, from Stabilization Ponds	Truck	5.30	5.55	0.6
	Offsite	Filter Cake + Ash Soil-like or Treated	Rail	1.95	6.50	0.7
		Treated, from Stabilization Ponds	Rail	5.60	8.70	0.9
Underground (hydraulic fill)	Onsite	Thickener Underflow	Pipeline	1.05	3.20	0.35
	Offsite	Filter Cake + Ash	Rail	1.75	8.20	0.85

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[a] Not including costs for monitoring or sludge processing (see text).

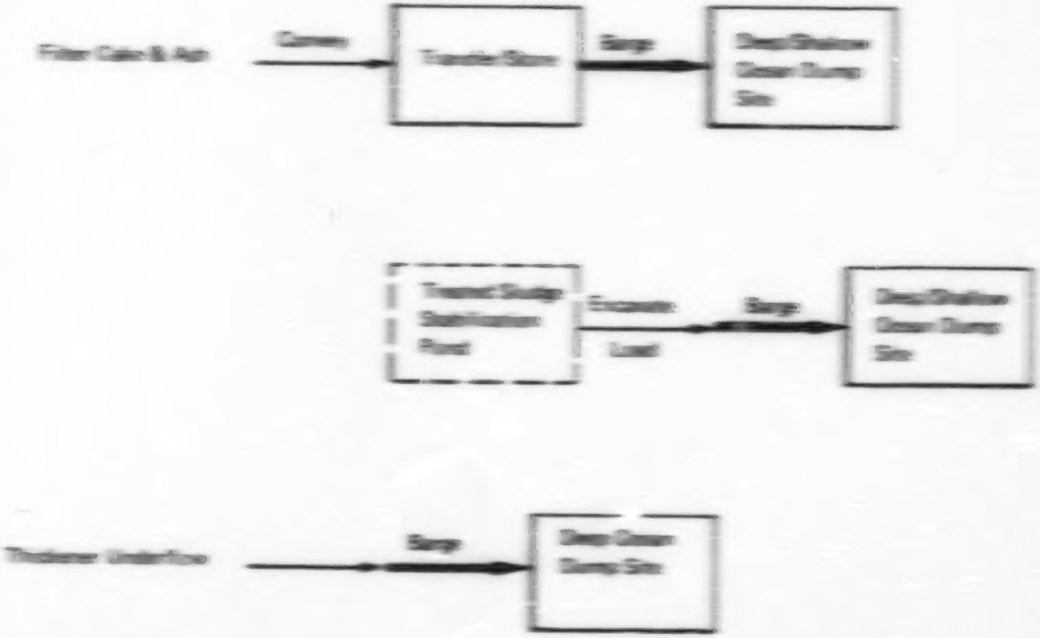
Filter Cake & Ash
Convey
Transfer Station
Barge
Deep/Shallow Ocean Dump Site
Treated Sludge Stabilization Pond
Excavate
Load
Barge
Deep/Shallow Ocean Dump Site
Thickener Underflow
Barge
Deep Ocean Dump Site

FIGURE VII-3 OCEAN DISPOSAL OPERATIONS

On-shelf disposal sites have been assumed to be 35 nautical miles (nmi) offshore, and off-shelf disposal sites to be 100 nmi offshore. In all cases, bottom-dump disposal has been assumed. While slurry dispersal is possible, it is more expensive both to transport the slurry and pump discharge the sludge. Transport of relatively dry filter cake and reslurry at sea prior to disposal is not considered practical due to the large pumping capacities required onboard.

It has been assumed that the sludge is produced in a power plant with ready access to the ocean. Thus, facilities for berthing barges would be available; however, a sludge transfer/storage facility would still be required.

In developing system costs for ocean disposal operations, the same sludge production rates have been used as in the mine disposal cases. While no assumptions have been explicitly made concerning the chemical nature of the sludge, implicit in the quantity and moisture content of the sludge is the assumption that the sludge is sulfite-rich. Since disposal of sulfite-rich sludges is not presently considered promising, quantities based upon sulfate-rich material would be more appropriate. The adjustment in total quantity handled could amount to as much as a 30% decrease due to the generally enhanced dewatering properties of sulfate-rich sludges. This lower total quantity would reduce the disposal cost (although not by a proportionate amount).

1. Description of Systems

a. On-Shelf Disposal

Two cases are considered for on-shelf disposal--bottom dumping of treated, brick-like sludge and untreated filter cake with fly ash. While disposal of untreated sludge on the continental shelf is not presently considered to be a promising alternative (either for sulfite-rich or sulfate-rich) it is included for comparative cost purposes.

The disposal operation for on-shelf disposal would be almost identical for treated and untreated (filtered) sludge, except that treated sludge is assumed to require excavation of the treated material from stabilization ponds as previously described (in order to produce the brick-like material). The excavated sludge or filter cake admixed with fly ash would be conveyed to a storage/transfer area for intermediate storage and loading of the barges. A storage/transfer system involving a hopper feeder has been assured, a system similar to that used for loading rail cars. However, the transfer system can vary considerably depending upon the distance between the power plant and the dock and the type of docking facilities available. In many cases, an overhead crane might be more appropriate for loading barges.

The sludge could be transported either by a tug/barge combination or by a self-propelled ship. A 500-megawatt power plant producing 365,000 tons of dry sludge (filter cake plus ash) would require one tug and two barges for an on-shelf dump, using a nominal cycle time of 18 hours for each barge and a 14-hour cycle time for the tug. Only one self-propelled ship would be required. Due to its greater speed (10 knots versus 5 knots for the tug/barge), the self-propelled ship would have a total cycle time on the order of nine hours under normal conditions. In both cases the system would need to be designed with the capacity to handle short-term peaks in sludge production and interruptions due to inclemental weather. Hence, both the self-propelled ship and each barge should be sized to handle about 2,500 tons of sludge, and the storage area would need to be sized for about a one-week inventory of sludge.

b. Off-Shelf Disposal

The system design and operation for deep ocean disposal of filtered (or treated) sludge would be basically the same as that for on-shelf disposal. The principal difference would be in the longer cycle times owing to the greater transport distance (120 nmi versus 25 nmi). Therefore, the number and/or capacity of the units would be greater. For deep ocean disposal two tugs and three barges (48-hour cycle time) or two self-propelled ships (~24-hour cycle time) would be required. These would have the same capacities (2,500 tons) as in the on-shelf disposal case for handling filter cake (with ash). Larger units could be built, but this would decrease system flexibility.

Since disposal of untreated material (particularly sulfate-rich) off the shelf appears to be more environmentally acceptable, dumping of partially settled thickener underflow has also been considered. Thickener underflow (~35-40% solids) would require larger barges and ships (3,500 tons versus 2,500 tons); hence, higher transport costs. There would be some cost savings in that the transfer system between the FGD system and the barge or ship could be quite simple (at the extreme, just a pipeline), and there would be no need of filtration equipment. However, these cost savings would be offset by higher transport costs and some type of sludge storage area, such as an additional barge, to supplement the thickener.

3. Disposal System Costs

Table VII-5 summarizes the capital and operating costs for bottom-dump disposal of sludge. These estimates include only the costs incurred in handling and disposing the sludge in the form indicated. Processing costs such as admixing fly ash with filter cake, conversion to sulfate, or treatment (except excavation) are not included. Monitoring costs also are not included. Monitoring costs can be highly variable depending upon ocean depth, environment, species, or parameters monitored and frequency of dumping. They will, however, be a significant, if not a major, cost factor. Assuming two to three monitoring cruises per year (not including baseline monitoring), monitoring costs could run between $500,000 and $1,000,000/year for on-shelf disposal and twice this amount for off-shelf disposal. As in the case of mine disposal, monitoring costs would not be a direct function of the quantity of sludge dumped, and therefore it would not be appropriate to include these costs directly in the operating cost estimates. The same costs could be incurred with an order of magnitude increase in the quantity of sludge dumped.

In all cases the costs for operating a self-propelled ship disposal system are lower than those for the tug/barge combination due to the lower capital investment (fewer ships due to shorter cycle times). The cost difference, as would be expected, is much greater for the deep ocean disposal where the proportion of travel time to port time increases. For deep ocean disposal the self-propelled ship is also favored because it is more seaworthy and hence less affected by climatological conditions.

In general, disposing of filter cake (with ash) on the shelf runs $4.00-5.00 per dry ton of sludge, and disposal of treated sludge runs about $2.00-2.50 per dry ton more due to excavation costs. Deep ocean disposal runs about $3.00-4.00 per dry ton more than shallow ocean disposal for similar materials.

TABLE VII-5

CAPITAL AND OPERATING COSTS FOR OCEAN DISPOSAL ALTERNATIVES

(Bottom-Dump Disposal)

Ocean Locale	Sludge Type	Transport Mode	Capital Cost ($MM)	Operating Costs[c] ($/dry ton)	Operating Costs[c] (mills/kwh)
Continental Shelf (25 nmi)	Filter Cake + Ash (50% solids)[a]	Tug/Barge	3.7	4.90	0.5
		Self-Propelled Ship	3.2	4.15	0.4
	Treated, from Stabilization Ponds	Tug/Barge	7.4	7.20	0.7
		Self-Propelled Ship	6.9	6.35	0.6
Deep Ocean (100 nmi)	Filter Cake + Ash[b] (50% solids)	Tug/Barge	7.25	8.90	0.85
		Self-Propelled Ship	5.3	6.85	0.65
	Thickener Underflow (15% solids)[b]	Tug/Barge	7.95	10.05	0.95
		Self-Propelled Ship	5.80	8.05	0.75
	Treated, from Stabilization Ponds	Tug/Barge	7.25	11.10	1.05
		Self-Propelled Ship	5.3	9.05	0.85

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[a] Not considered promising.

[b] Only considered promising for sulfate-rich sludge at the present time.

[c] Costs do not include monitoring which can run $500,000-$1,000,000/year for two to three monitoring cruises per year. Such costs are not a direct function of the quantity of sludge.

Disposing of thickener underflow will be more expensive than disposing of a dry, untreated material due to the overriding capital costs for the ocean transport systems. In order to properly compare overall disposal costs, sludge processing costs (filtration, oxidation, treatment, admixing, etc.) need to be included. If untreated sludge can only be disposed of as a sulfate-rich material, then it may also be necessary to include the entire FGD system, since oxidation may be most practically accomplished as an integral part of the FGD operation.